HIGH SCHOOL

PHYSICAL SCIENCE

PART II

REVISED EDITION

MERCHANT

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HIGH SCHOOL

PHYSICAL SCIENCE

PART II

REVISED EDITION

FOR MIDDLE SCHOOL CLASSES IN SECONDARY SCHOOLS

BY

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PREFACE.

The revised edition of the High School Physical Science, Part II., is designed to cover the courses in Sound, Light, Magnetism and Electricity prescribed for the Middle School.

To make the treatment continuous, references are inserted wherever articles from Part I. are to be read in connection with this work.

A few topics not named in the Departmental Course of Study have been included on account of their practical interest or their bearing on the present reconstruction of physical and chemical theories. The student who desires to confine himself strictly to the curriculum may omit pages 223–232, and pages 244, 245.

I am indebted to Mr. F. W. C. McCutcheon and Mr. A. W. Keith, of the London Collegiate Institute, for assistances in reading the proof sheets.

F. W. MERCHANT.

LONDON, *16th April, 1906.*

CONTENTS.

PHYSICAL SCIENCE

PART II.

CHAPTER I.

ORIGIN AND TRANSMISSION OF SOUND.

We have learned, Chapters XII. and XIII., Part I., that sound has its origin in the vibrations of some vibrating body and is transmitted from the centre at which it originates by some material medium, which may be a solid, a liquid or a gas. We shall now examine more closely the nature of this vibratory movement and the theory of its transmission by an elastic medium.

1. Simple Harmonic Motion.

Experiment 1.

Suspend a small heavy ball (a lead bullet answers well) by a thread, which should be as long as practicable. Set it revolving in a circle (Fig. 1).

Is the number of times which it revolves the same during equal intervals of time?

Bring the eye on a level with the ball, when it will **appear** to move to and fro in a straight line. Study the motion carefully.

When does the ball appear to be at rest? When does its speed appear to be greatest? When does its speed appear to be increasing? When decreasing?

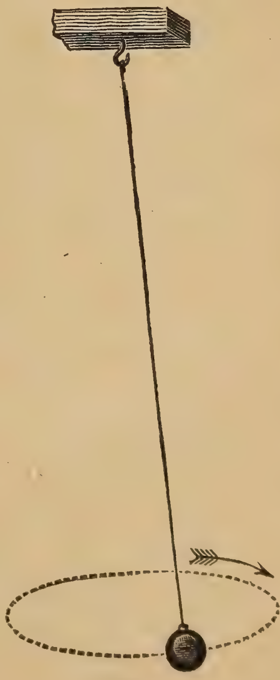


FIG. 1.

Draw a circle (Fig. 2) to represent the path of the ball, and divide the circumference into any number of equal parts, say twelve, *ab*, *bc*, *cd*, etc. Through the points of division draw perpendiculars to the line AG, the distances AB, BC, CD, etc., being the projections on AG of the equal arcs *ab*, *bc*, *cd*, etc.

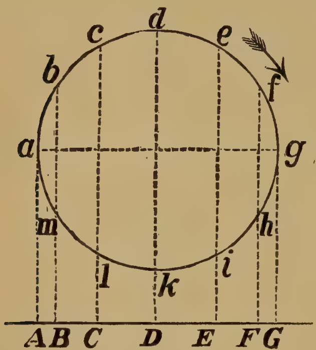


Fig. 2.

If the ball makes a complete revolution in one second,

(1) How long does it take it to pass from *a* to *b*, *b* to *c*, etc.?

(2) How long does it take it in appearing to pass from A to B, B to C, etc.?

When a body vibrates along a straight line, as the ball in the above experiment appears to do, in such a manner that its position at any moment is the same as the projection on that line of a point moving uniformly in a circle whose diameter is the length of the line, it is said to move with **simple harmonic motion.** The motion is so named because all musical sounds are caused by bodies vibrating in this way.

Motion from left to right is regarded as **positive,** and from right to left **negative.**

The extent of the excursion of the vibrating body on either side of its middle point is called its **amplitude.** It corresponds to the radius of the circle of reference.

The interval of time between two successive passages of the vibrating body through a given point in its path in the same direction is called its **period.** The fraction of a whole period which has elapsed since the particle

last passed through the middle point of its range in the positive direction is called the **phase.**

2. Wave-Motion.

Before proceeding to consider the theory of the transmission of sound by elastic bodies, it will be necessary for the student to become familiar with the phenomena of wave-motion in general.

Let a pebble drop into a body of water at rest, and observe the motion of the water.

Observe

(1) That a depression is produced at the point where the stone touches the water.

(2) That this depression travels outward from this point as a circular trough.

(3) That the depression of the water at the point where the stone dropped is followed by an upward movement of the water at this point, causing a ridge or crest.

(4) That this crest travels after the depression, moving at the same rate in a circle concentric with it.

(5) That this crest is followed by another depression, and the depression by another crest, and so on, thus producing a series of ripples or waves.

Throw a piece of wood on the water, and note that it moves up and down, thus showing that, while the waves move outward in a horizontal direction, the particles vibrate vertically.

FIG. 3.

Experiment 2.

Fasten one end of a light chain about eight feet long to the ceiling (Fig. 3). By giving the lower end of the chain a number of quick jerks, send a series of pulses along the chain.

1. In what direction are the waves in the chain propagated?
2. In what direction do the individual links of the chain move?

The transmissions of the disturbances in the water and the chain furnish examples of wave-motion. A wave in its simplest form consists of a series of particles all vibrating in simple harmonic motion and having between them a uniform difference of phase. Consider, for example, a number of particles all made to vibrate with simple harmonic motion along the vertical lines A, B, C, etc. (Fig. 4), so that each succeeding particle begins to move $\frac{1}{12}$ of a period behind the other. To determine the posi-

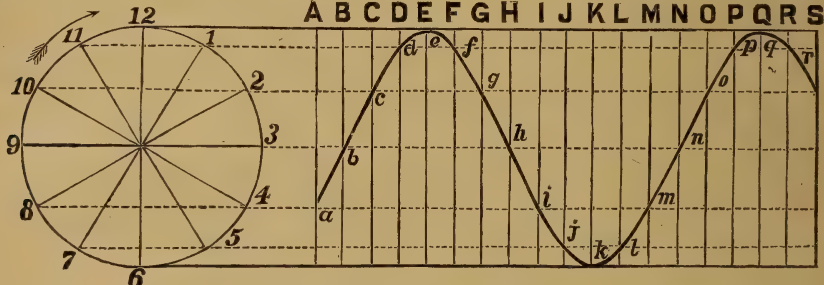


FIG. 4.

tions of the particles at equal intervals of time draw a circle whose radius is the amplitude of vibration, divide it into twelve equal parts, and through the points of division draw lines perpendicular to the lines A, B, C, etc. Then these lines will mark off on the lines A, B, C, D, etc., spaces which the vibrating particles traverse in $\frac{1}{12}$ of a period. Suppose the particle in A to be at *a*, corresponding to *4* in the circle, then as the particle in B is $\frac{1}{12}$ of a period behind, it will be at *b*, corresponding to *3* in the circle, and the particle in C, which is $\frac{2}{12}$ of a period behind that in A, will be at *c*, corresponding to *2* in the circle. Similarly the positions of the particles in the other lines are determined to be at *d*, *e*, *f*, etc.

Through these points trace a smooth curve, representing the wave form.

Trace curves to show the positions of these particles, $\frac{3}{12}$, $\frac{6}{12}$, $\frac{9}{12}$ and $\frac{12}{12}$ of a period later, and interpret them.

The distance from any particle in the wave to the next one in the same phase, for example from *e* to *q*, *c* to *o*, or *a* to *m*, is called the **wave-length.** In other words, the wave-length is the distance traversed by the wave during one vibration period.

3. Transverse Waves.

Waves, like those of the water or the chain, **which are produced by the vibratory motion of particles at right angles to the direction in which the wave is propagated, are called transverse, or crest-and-hollow, waves.**

4. Longitudinal Waves.

Experiment 3.

Make a "wave machine" similar to that illustrated in

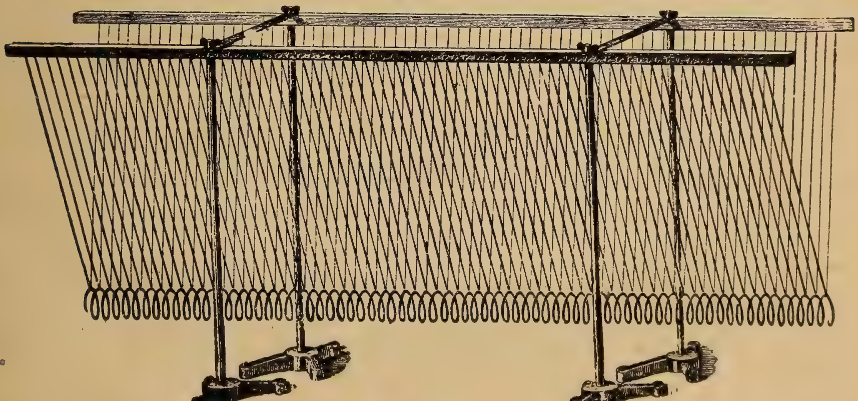


FIG. 5.

Fig. 5. The spiral should be 2 metres long and 7cm. in diameter, and be made of 72 turns of No. 12 copper wire.

The spiral may be made by winding the wire uniformly around a cylindrical rod, and then removing the rod.

The threads by which the spiral is suspended should be 60cm. long. The frame should be made light and stiff.

Take hold of the end of the spiral and give it a quick jerk outward in the direction of the axis, and then let go. Observe the pulse as it moves along the spiral.

How do the separate coils move?

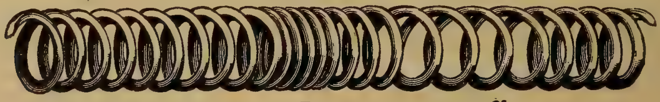
Take hold of the end of the spiral again, push it inward, let go quickly, and again observe the pulse as it moves along the spiral.

How do the separate coils now move?

Insert the blade of a knife between the coils near one end of the spiral, rake it quickly towards the other end across a few turns of the wire, and observe the motion of the wave along the spiral.

In the first case, when the spiral was jerked outward, the coils appeared to move backward in a direction opposite to that in which the pulse is moving, thus forming what is called **a pulse of rarefaction.** In the second case, when the spiral was pushed inward, the coils appeared to move forward in the direction in which the pulse was moving, forming **a pulse of condensation.**

In the third case a pulse of condensation (Fig. 6 B) is



A *B* *C*

FIG. 6.

followed by a pulse of rarefaction (Fig. 6 C), and a double pulse, or wave, is formed.

It will be observed that while the wave moves along the spiral, each individual turn of wire simply moves backward and forward in the line of direction of the wave.

Waves which are produced by the vibratory motion of particles along the lines in which the waves are propagated are called longitudinal waves.

The wave-length in this case is the distance between two successive centres of condensation or between two successive centres of rarefaction.

5. Theory of the Transmission of Sound by an Elastic Medium.

Experiment 4.

Take a tin tube about 3 metres long and 10 cm. in diameter one end of which tapers to a diameter of about 2.5 cm. (Fig. 7)

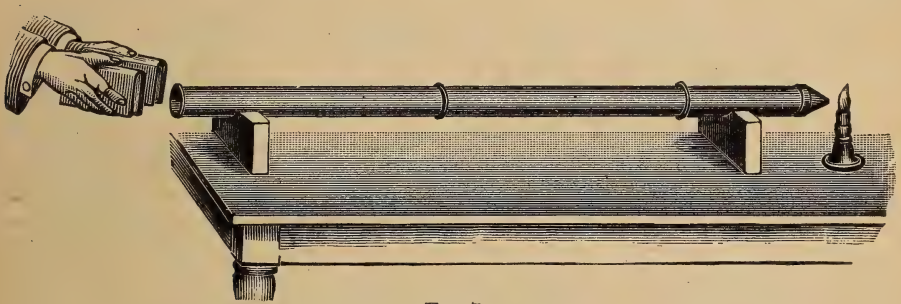


FIG. 7.

Tie over the large end a paper membrane and in front of the small end place the flame of a lighted candle. Strike two books together in front of the membrane. Tap the membrane.

1. How is the flame affected?

2. How do you know that the effect is not due to a current of air?

3. What is the cause of the effect noted?

To answer the last question compare the air as an elastic medium with the coil spring (Experiment 3) and consider the following questions:—

(*a*) How will the sudden forward motion of the membrane affect the air in the tube immediately in front of it?

(*b*) Will this air remain in its changed condition? If not, why will its condition be again changed, and how, in changing its condition, will it affect the air beyond it?

(*c*) How does the motion of the individual particles of air within the tube differ from the movement of the disturbance as it passes from one end of the tube to the other?

Experiment 5.

Wet a piece of linen paper and paste it over the mouth of a tumbler. When the paper has become dry, cut away a part of it, as shown in Fig. 8, making a small opening at first and

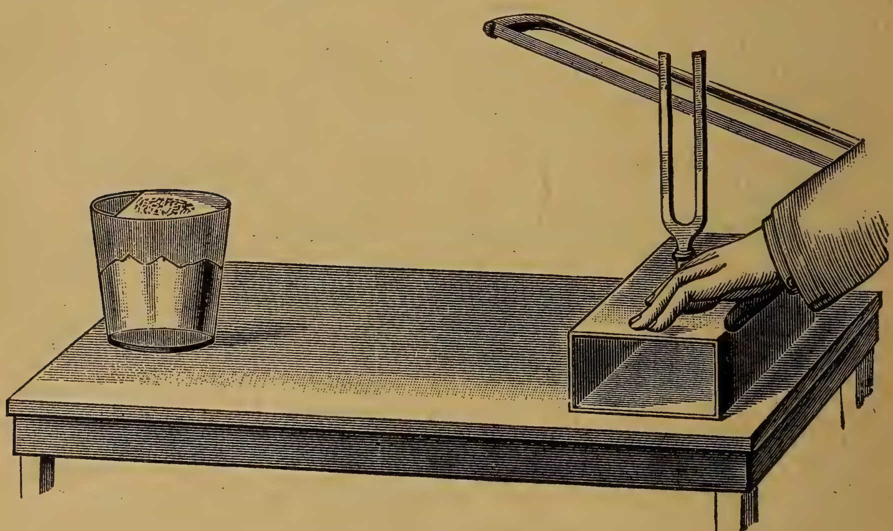


FIG. 8.

gradually increasing its size until the tumbler gives forth a loud sound when a vibrating tuning-fork is held over the opening. Sprinkle fine sand on the paper, mount the fork on a resonance-box, and sound it at a distance from the tumbler.

1. What effect has the sounding of the fork on the sand placed on the paper?

2. What evidence have you that the paper is vibrating?
3. How are the vibrations of the fork transmitted to the paper?

It is evident from the foregoing experiments that the vibrations of a sounding body are transmitted by the air in a species of wave-motion.

The waves are believed to be of a form similar to those which pass along the spiral spring (Experiment 3, page 5), when one of the coils is disturbed.

Take, for example, the nature of the disturbances set up in the air by a tuning-fork.

As one of the prongs of the vibrating fork swings swiftly forward, it compresses the air immediately in front of it (Fig. 9). This air, on account of its elasticity, resists the compression, and its tendency to

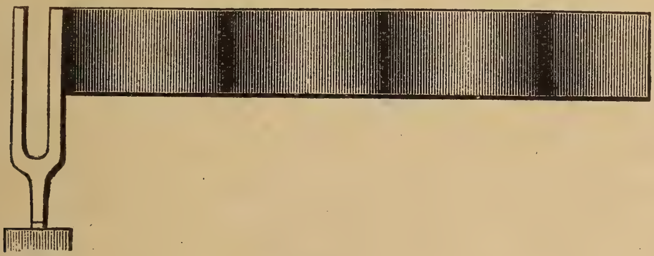


FIG. 9.

expand causes the air in front of it to be compressed. This air in turn compresses that in front of it, and thus a pulse of condensation travels forward through the air from the prong of the fork. In the meantime the prong of the fork swings backward, and the air behind it is rarefied. A pulse of rarefaction is thus produced, which follows immediately the pulse of condensation.

This in turn is followed by a pulse of condensation, which again is followed by one of rarefaction, and so on.

These alternate pulses of condensation and rarefaction constitute a regular series of sound-waves, which pass in succession through the air, and, falling upon the ear, are the condition of the sensation of sound.

The vibration of all other sonorous bodies set up similar waves, which pass outward in every direction from the body, like a series of ever-enlarging concentric spherical shells (Fig. 10).

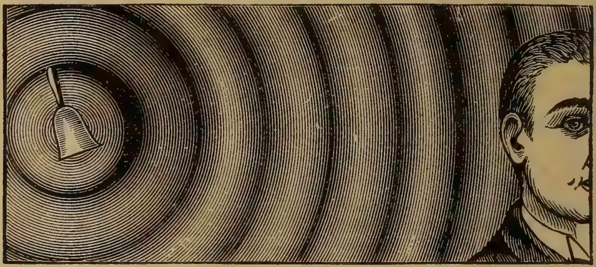


Fig. 10.

The student must be careful not to confound the motion of the wave with the motion of the air particles which constitute it at any instant. **While the wave moves constantly forward, the air particles simply move backward and forward in the direction of the wave.**

Since a single wave is made up of a pulse of condensation and a pulse of rarefaction, **each aerial particle makes one complete vibration while the wave progresses one wave-length.**

To get a clear conception of the propagation of sound-waves and the motion of the individual particles which compose them, repeat the experiment with the coil spring. Also perform the following experiment.

Experiment 6.

Cut a slit AB in a piece of black cardboard as shown in Fig. 11*a*. Place the slit over the dotted line in Fig. 11*b*, and draw the book from under it in the direction of the arrow, keeping the slit always at right angles to the side of the page.

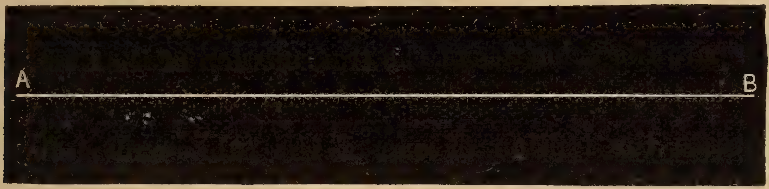


Fig. 11*a*.

Observe the propagation of the waves of condensation and rarefaction as they appear at one end of the slit and pass along in the direction of the other. Also observe the to-and-fro motion of the individual small white dashes in the direction of the slit.

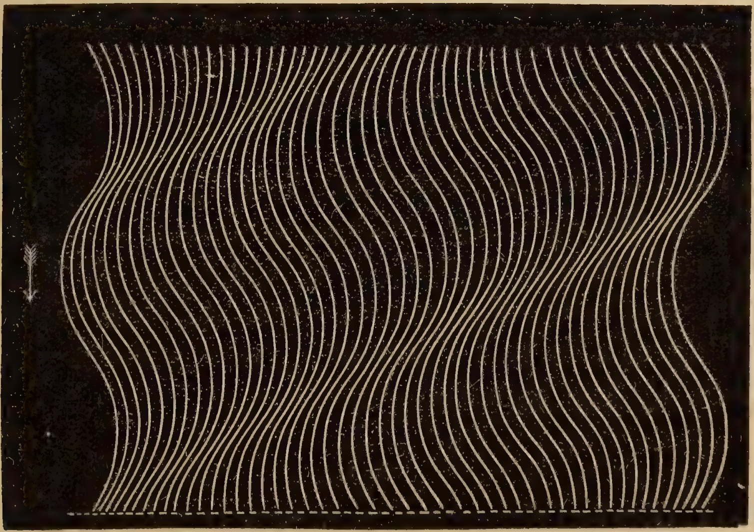


Fig. 11*b*.

Liquids and gases are believed to transmit sound by waves of condensation and rarefaction in exactly the same way as air.

6. Upon what does the Velocity of Transmission of a Wave in an Elastic Medium Depend?

Experiment 7.

Stretch side by side with equal tension two similar rubber tubes, about 3 metres long. Strike the tubes with a ruler a short distance from one end, causing a depression in each.

Compare the velocities of the transmission of the depression along the tube.

Increase the tension of one of the tubes and strike the tubes as before.

Compare the velocities of transmission.

Remove one of the tubes, fill it with sand and stretch it beside the other with equal tension. Strike the tubes again with the ruler, and again compare the velocities of transmission.

Upon what properties of the tube does the velocity of transmission of wave-motion depend?

7. Velocity of Sound Dependent on the Elasticity and the Density of the Medium.

Newton demonstrated that the velocity of propagation of a wave through any medium varies directly as the square root of the coefficient of elasticity of volume, and inversely as the square root of the density. According to this law the velocity of sound-waves will be given by the equation

$$V = \sqrt{\frac{E}{D}}$$

where V denotes the velocity of the sound, E the coefficient of elasticity, and D the density of the medium.

The greater the elasticity and the less the density of the medium, therefore, the more rapidly is sound transmitted by it.

Since the density of a solid or a liquid is greater than that of a gas, sound would naturally travel more slowly through these forms of matter than through gases, were it not that the increase in velocity due to their greater elasticities more than compensates for the decrease in velocity due to increase in density. Hence sound-waves generally travel faster in solids and in liquids than in gases.

8. How do changes in the Temperature and in the Pressure of the Atmosphere affect the Velocity of the Transmission of Sound by it?

1. If a given mass of gas is confined within an enclosed space and then heated, what change will take place in (*a*) the density, (*b*) the elasticity of the gas? What effect will these changes have upon the velocity with which the gas transmits sound?

2. If the same gas is heated when it is free to expand, what changes in density and elasticity will take place, and what difference in its conducting power will be observed? Explain.

3. How does an increase in the temperature of the air, the pressure remaining constant, affect the velocity with which sound is transmitted by it? Explain.

4. If a given mass of gas is confined within an enclosed space and its volume is (1) decreased, (2) increased, while the temperature is kept constant, what change will take place in (*a*) the density, (*b*) the elasticity of the gas in each case? What is the relation between the change in elasticity and the change in density? (See Part I., page 119.) What changes, if any, will take place in the velocity of sound transmitted by the gas?

5. What changes in the velocity of sound transmitted by the air accompany (1) a rise in the barometer, (2) a fall in the barometer, the temperature of the air remaining constant? Explain.

If the above questions are carefully considered it will be understood that a change in the height of the barometer, the temperature remaining constant, is not

accompanied by a change in the velocity of the transmission of sound by the atmosphere, because the elasticity and the density change in the same ratio, but that a change in the temperature of the atmosphere, the height of the barometer remaining constant, affects the velocity of the transmission of sound, because the elasticity remains constant while the density varies inversely as the absolute temperature. (See Charles' Law, Part I., page 203.) For example, if the temperature of the atmosphere changes from 17°C to 27°C, the density decreases in the ratio (273 + 27) : (273 : 17), or 30 : 29. Hence the velocity of sound increases in the ratio

$$\sqrt{29} : \sqrt{30}.$$

9. Determination of the Velocity of Sound in Air.

The velocity of sound in the air may be approximately determined in the following manner. The distance between two stations is measured. A gun is fired at one station, and the interval of time elapsed between the seeing of the flash and the hearing of the report at the other station is observed. The distance between the stations and the time taken by the sound to travel between them being known, the velocity of sound in the air can be determined. It is assumed that the time taken by the light to pass from one station to the other is so short that it may be neglected.

To allow for the action of the wind, the firing should be done at alternate stations, and the average of several results taken.

The above method will at best give but an approximate result. The method devised by Regnault for determining the velocity of transmission by gases enclosed in tubes gives a much more accurate determination.

A pistol is fired at one end of a long tube of known length, and an electrical recording apparatus registers automatically the time that elapses between the pulling of the trigger of the pistol and the making of a mark by a pointer attached to a membrane, which, placed at the other end of the tube, vibrates when the sound-pulse reaches it. Data are thus furnished for calculating the velocity of the sound transmitted by the air in the tube.

The velocity of sound in any other gas may be determined in the same manner with this apparatus. The air is exhausted and the tube filled with the gas.

When the temperature is 0°C, the velocity of sound in the air is about 1090 feet per second, and the velocity increases about two feet per second for each increase in one degree centigrade in temperature.

10. Determination of the Velocity of Sound in a Liquid and in a Solid.

Since the coefficients of elasticity and the densities of liquids and solids can be determined experimentally, the velocity of sound in these forms of matter can be determined theoretically from the equation.

$$V = \sqrt{\frac{E}{D}}$$

The results are found to agree closely with experimental determinations when these are possible.

The velocity of sound in water is about $4\frac{1}{2}$ times its velocity in air.

11. Relation among Velocity, Vibration-Number, and Wave-Length.

The particles composing a sound-wave make one complete vibration while the sound-wave travels one wave-

length; therefore, if n denotes the number of vibrations in a unit of time, and λ the wave-length of the sound-wave, the sound travels a distance of $n\lambda$ in a unit of time, or

$$v = n\lambda$$

where v denotes the velocity of the sound.

Hence

The velocity = the vibration-number × wave-length.

This relation gives a method of determining the velocity in air when the vibration number and the wave-length are known. (See Art. 11, page 30, and Art. 2, page 47).

QUESTIONS.

1. It is found that when a cannon is placed on ice at a distance from the shore and fired, persons on shore hear two reports. Explain the reason.

2. A tube, 1000 feet long, is filled with oxygen gas. Find how quickly the report of a pistol fired at one end of the tube will pass to the other, if the density of oxygen is 16 times that of hydrogen, and the velocity of sound in hydrogen is 4200 feet per second, when the pressure of the hydrogen is the same as that of the oxygen.

3. At which place has sound the greater speed—at the foot of a mountain or at the top? Why?

4. If the velocity of sound in the air at 0°C is 1090 feet per second, find:

   (1) The speed in air at a temperature of (*a*) 7°, (*b*) 10°, (*c*) 20°.

   (2) The velocity in carbon dioxide at 0°C if its density is 1.5 times the density of air.

   (3) The velocity in hydrogen at 0°C if the density of air is 14.5 that of hydrogen.

   (4) How long it will take sound to traverse a distance of one mile in air when the temperature is 16°C.

5. What must be the temperature of the air in order that sound may have a velocity double that at 0°C ?

6. If the speed of sound in the air is 340 metres per second at 16°C, what will the speed be at a temperature of 168°C if the pressure of the gas is doubled ?

7. How long will it take the sound of a signal gun to reach an observer 3.2 miles away when the temperature of the air is 18°C ?

8. Two stations are 61045 feet apart, and the report of a gun fired at one station is heard at the other 54.6 seconds after the flash is seen. What is the velocity of the sound in the air ?

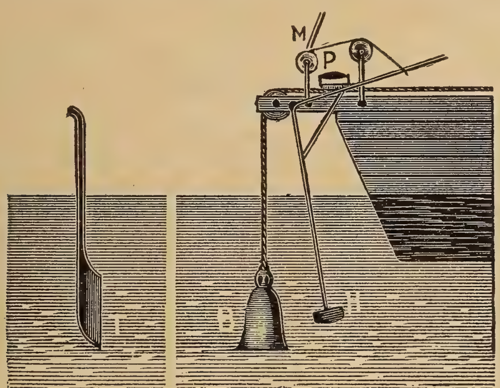


FIG. 12.

9. Two boats were stationed on Lake Geneva, 51700 feet apart. One boat was supplied with a bell B placed under water (Fig. 12), and so arranged as to be struck by a hammer H at the same instant that a torch M turns over and lights the gunpowder P. The sound of the bell was heard at the other boat, by means of trumpet T placed in the water, just 11 seconds after the flash of the gunpowder was seen. What was the velocity of sound in the water ?

10. A report of a cannon is heard 6 seconds after the flash is seen. If the temperature of the air is 15C., what is the distance of the observer from the cannon ?

11. How do you account for the fact that the time required for a sound to travel a certain distance differs from day to day ?

12. If all the soldiers in a long column keep time to the music of a band, will they step together ?

13. A number of soldiers are drawn up in the form of a circle, and each man fires his gun at the instant a signal is given by a man placed at the centre of the circle. Will the sound appear as a single report to any of the men? Explain.

14. If a tuning-fork which vibrates 256 times per second sets up in the air sound-waves the wave-length of which is 52 inches, what is the velocity of sound in the air?

15. It is observed that the velocity of a sound produced by a tuning-fork whose vibration-number is 435, is 1100 feet per second, what is the wave-length of the sound-waves?

CHAPTER II.

INTENSITY, REFLECTION, REFRACTION AND INTERFERENCE OF SOUND-WAVES.

I.—Intensity of Sound.

1. Intensity and Amplitude of Vibration.

Experiment 1.

Repeat Experiment 1, page 160, Part I. Observe the string, and note the changes in the amplitude of its vibrations.

What change takes place in the amplitude of the vibration of the string as the sound grows weaker?

Experiment 2.

Repeat Experiment 5, page 162, Part I. Observe the tracing on the smoked glass.

What evidence have you that the intensity of the sound increases with the amplitude of vibration of the sonorous body?

The intensity of a sound-wave is measured by the energy of the vibrating particles. When the vibration-number remains constant, the velocity varies as the amplitude of vibration; for example, if the vibrating particles have twice as far to swing in the same time, the velocity must be doubled; but the energy varies as the square of the velocity (Part I., page 78), therefore the **intensity of a sound-wave varies as the square of the amplitude of vibration.**

2. Intensity and Density of the Medium.

Experiment 3.

Repeat Experiment 1, page 167, Part I.

1. What change takes place in the density of the air in the receiver as the exhaustion proceeds?

2. What change in intensity of the sound accompanies this change in density?

The intensity of sound-waves increases with the density of the medium in which they originate.

If the intensity of the sound-wave is measured by the energy of vibrating particles, why should its intensity be affected by changes in the density of the medium in which it originates?

3. **Intensity and Distance.**

It is a matter of common experience that the intensity of a sound decreases with an increase in the distance from the point at which it originates. The exact law will be learned from the following considerations.

As we have seen (page 10), a sound-wave is spherical in form.

When the radius is unity, the surface is 4π.

"	"	2	"	16π.
"	"	3	"	36π.
"	"	etc.	"	etc.

But each of the surfaces 4π, 16π, 36π, etc., receives the same amount of energy, therefore the energies received by a unit surface are proportional to $\frac{1}{4\pi}$, $\frac{1}{16\pi}$, $\frac{1}{36\pi}$, etc., or to 1, $\frac{1}{4}$, $\frac{1}{9}$, etc., when the distances are in the proportion 1, 2, 3, etc.

Hence

The intensity of a sound-wave varies inversely as the square of the distance from its source.

QUESTIONS.

1. The workmen engaged in constructing the St. Clair tunnel observed that when working in an atmosphere of compressed air, the tones of ordinary conversation appeared abnormally loud. Explain the reason.

2. Why are sounds produced on high mountains of diminished intensity?

3. Will an increase in the vibration-number cause an increase in the intensity of a sound-wave if the amplitude of vibration remains constant? Give reasons for your answer.

4. A cannon is fired at a point half way up a mountain. Will the report reach two observers with equal intensity, if one observer is at the top of the mountain and the other at the foot? Give reasons for your answer.

5. If two cannons, charged equally, are fired, one at the top of a mountain, and the other at the foot, will the reports come to a person stationed half way up the mountain with equal intensities? Give reasons for your answer.

6. If a small bell is placed over water in a flask, as shown in Fig. 13, the sound of the bell can be distinctly heard when the flask is corked; but if the water is boiled, the lamp removed, and the flask corked while the steam is still issuing from its mouth, the sound of the bell can scarcely be heard after the flask has cooled. Explain the reason.

Fig. 13.

7. If A is 500 yards from a cannon when it is discharged, and B 1000 yards, compare the intensities of the sounds reaching A and B.

II.—Reflection of Sound.

4. Reflection of Sound from Plane Surfaces—Laws of Reflection.

Experiment 1.

Mount two tubes about 2 cm. in diameter on the arms of the reflection apparatus used in Experiment 2, page 261,

Part I. Connect one of the tubes with a reed pipe giving an acute sound, and support at the outer extremity of the other tube a sensitive flame (Fig. 14).

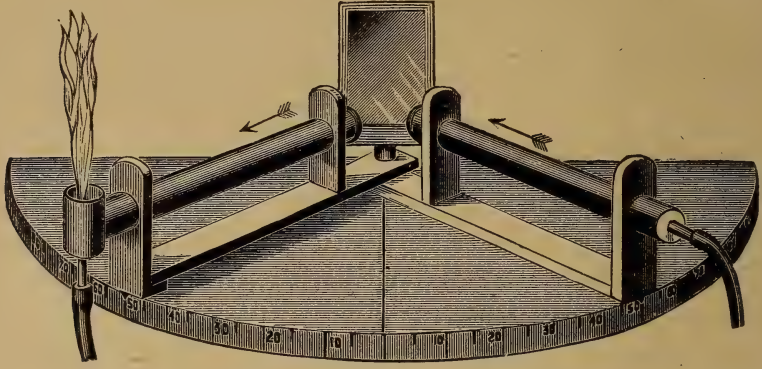


FIG. 14.

To make a nozzle for the sensitive flame, take a piece of glass tubing about 20 cm. long and 8 mm. in diameter, heat and draw it out as shown in Fig. 15 until the diameter is

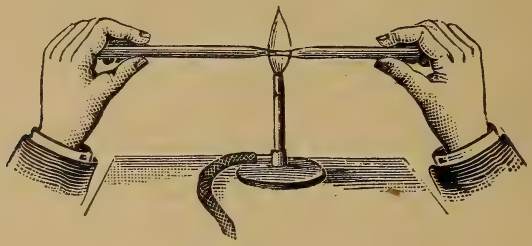


FIG. 15.

reduced to 2 or 3 mm. Cut the tube in the middle of the contracted portion by scratching it with a file. Connect one of the nozzles by means of a rubber tube with the gas supply. Turn on the gas and ignite it. If the pressure of the gas is just right, the flame thus produced will burn with a slight roaring and will take a form somewhat similar to A (Fig. 16); but if the flame takes the form shown in

B and burns quietly, the nozzle must be discarded and another one prepared. When a tube has been found which answers the purpose[1], turn off the gas gradually until the roaring just ceases and the flame takes the form of B. When the adjustment has been properly made, the flame becomes **sensitive,** and should change form in response to noises, especially of a shrill or a sibilant character. Test it by jingling a bunch of keys near it.

When a proper nozzle is prepared, pass it through a perforated cork, as shown in Fig. 16, and insert it into the reflection tube, as shown in Fig. 14. Fix the arm carrying the sensitive flame, sound the reed and move the arm supporting the pipe connected with it into a position in which the flame will be agitated. Repeat the experiment several times, placing the arm supporting the flame in different positions.

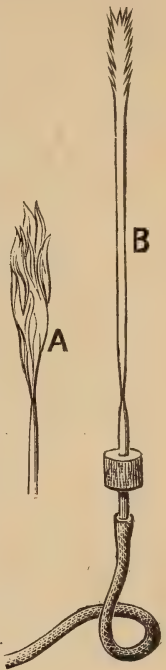


FIG. 16.

Compare the angles of incidence and reflection.

5. Reflection from Concave Surfaces.

Experiment 2.

Find the focus of a concave mirror by letting sunlight fall upon it, and noting the point in front of it at which a match is kindled. Suspend a watch at the focus of the mirror and place another similar mirror, facing it at a distance of 6 or 8 feet from it. Connect a glass funnel with your ear by means of a rubber tube, and place the funnel at the focus of the second mirror, with the mouth of the funnel towards the

---

[1] It is possible that in some laboratories the gas pressure may be too low to produce a sensitive flame. If so, the gas must be first collected in a gas holder and the supply for the nozzle taken from this source after the pressure has been adjusted.

mirror (Fig. 17). Place the end of the rubber tube in your ear and listen to the ticking of the watch. Now remove the second mirror and listen again.

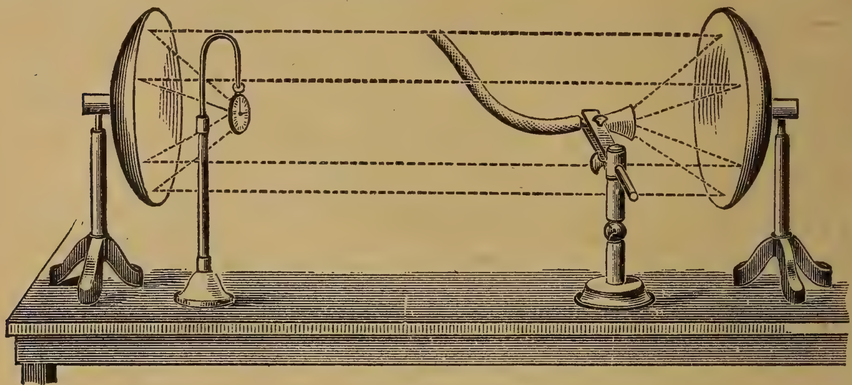


FIG. 17.

In which case is the ticking heard with the greater distinctness. Explain the reason.

This experiment explains the peculiar phenomena observed in **whispering galleries,** where a faint sound emanating from one point of a large room is heard distinctly at some distant point, while it is inaudible at points between them. The walls act as curved reflectors, and focus the sound-waves at the point.

6. Reflection by Change of Density.

Sound-waves are not only reflected by the surfaces of solids, but also by clouds, gas flames, etc.; and even in passing from a gas of one density to another of a different density they are in part reflected at the surface of separation. Whenever, therefore, sound-waves are propagated by a medium which is not of uniform density, they are more or less speedily dissipated by repeated reflections. Sound usually travels further at night than in the day-time because the air is more homogeneous.

Why is the air more homogeneous at night?

QUESTIONS.

1. A cannon is placed 550 yards from a long perpendicular line of smooth cliffs. An observer at a distance of 550 yards from the cliffs hears the cannon-shot 4 seconds after he sees the flash. If the velocity of sound is 1100 feet per second, when will he hear the echo from the cliffs?

2. A man standing before a high wall shouts, and hears the echo in five seconds. How far away is the wall if the temperature of the air is 16°C, the velocity of sound being 1090 feet per second at 0°C?

3. If a speaker can articulate distinctly but five syllables a second, what is the least distance from which a reflecting surface will send back a single syllable by echo, the temperature being 20°C?

4. What experiments would you perform to illustrate the fact that sound can be reflected from a layer of hot air?

III.—Refraction of Sound.

Experiment 1.

Fill a large toy balloon with carbon dioxide and suspend it from a support (Fig. 18). Place a loud-ticking watch near it.

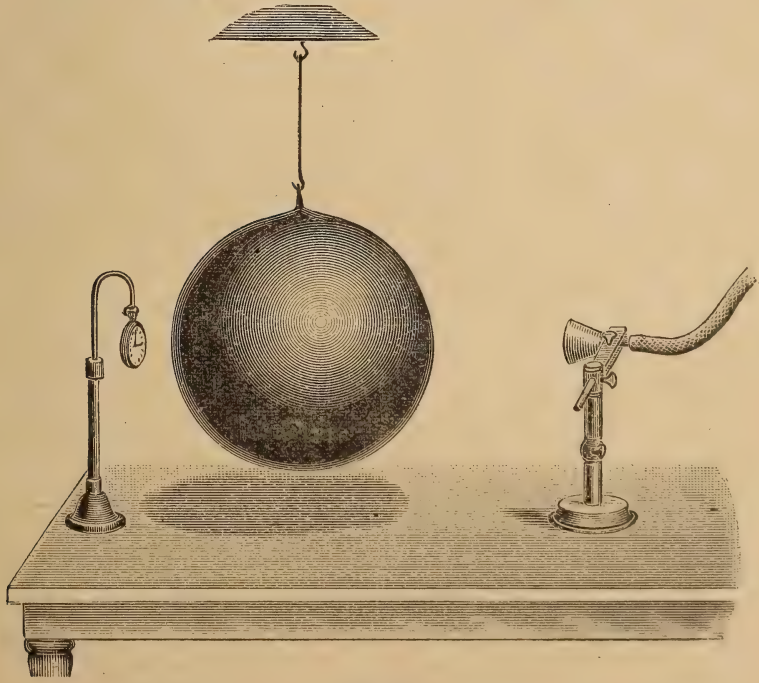


Fig. 18.

Bring the glass funnel used in Experiment 2, page 23, to face the balloon at various points on the opposite side.

1. Is there one point at which the sound can be heard much more distinctly than at points nearer or more remote? If so, how do you explain the phenomenon?

To answer the last question consider (*a*) which portions of the sound-waves falling on the balloon will be retarded the more, the middle or outer portions, (*b*) how this change in velocity of different portions of the waves affects their **form.**

2. If the balloon were filled with hydrogen instead of carbon dioxide how would it dispose of the sound-waves falling upon it? Why?

7. Refraction by Wind.

The observation that sounds heard with the wind are louder than those heard against it, is explained by the fact that the velocity of sound in the direction of the wind is increased by an increase in its velocity, while the velocity of sound in the opposite direction is retarded by an increase in its velocity. Since the velocity of the wind is less near the earth's surface than a little above it, the portions of sound-waves touching the earth's surface travel more slowly than those immediately above it; hence the waves are deflected downwards and the sound is condensed along the earth's surface if the sound is travelling in the direction of the wind, and are deflected upwards if the sound is travelling in the opposite direction.

IV.—Forced and Sympathetic Vibrations.

8. Forced Vibrations.

Experiment 1.

Suspend a heavy weight by a long cord. From this weight suspend a small weight, say a bullet, by a short thread. Set the system vibrating.

1. Describe the motion of the system, comparing the periods of vibration of the two pendulums.

2. How would the vibrations of the pendulums differ if they were suspended from separate supports?

The experiment furnishes an illustration of what are called **forced vibrations.** The heavy weight, on account of the superior energy which it possesses, forces its period of vibration on the small weight, which naturally would vibrate at a much faster rate.

The phenomena of consonance illustrated in Experiment 4, page 179, Part I., are explained in this way.

The top of the table is forced into vibration by the fork when the end of the handle is pressed against it. In the same way the sounding-board of a piano and membrane of a banjo are forced into vibration by the vibrations of the strings stretched over them. Similarly two bodies, whose periods of vibration are nearly alike, mutually affect each other. For example, two clocks which have nearly the same rate when at a distance from each other, will indicate the same time when placed side by side on the same support, the faster tending to accelerate the slower, and the slower to retard the faster. It is mechanically impossible to make a tuning-fork with prongs having exactly the same period of vibration, but the prongs of the fork vibrate in unison because they exercise mutual control.

9. Sympathetic Vibrations.

Experiment 2.

Place near each other two tuning-forks mounted on resonance boxes, and tuned to exact unison. Excite one of the forks, and after it has been vibrating for a few seconds stop it.

What is observed?

The experiment is an illustration of **sympathetic vibrations** in bodies with the same period of vibration. The result is due to the cumulative effect of the pulses produced in the air by the one fork in falling upon the other at intervals corresponding exactly to its period of vibration. The phenomena of resonance illustrated in Experiment 5, page 180, Part I., are due to this cause.

V.—Interference of Sound-Waves.

Experiment 1.

Take a cylindrical jar and, by pouring water into it, adjust its depth to re-sound to a tuning-fork held over it. Turn the fork around slowly on its axis, noting the changes in the loudness of the note as the fork is revolved.

At what position of the fork is the sound (*a*) the loudest, (*b*) the most feeble?

When the fork is in one of the positions where the sound grows weakest, cover one of the prongs with a small paste-board tube as shown in Fig. 19.

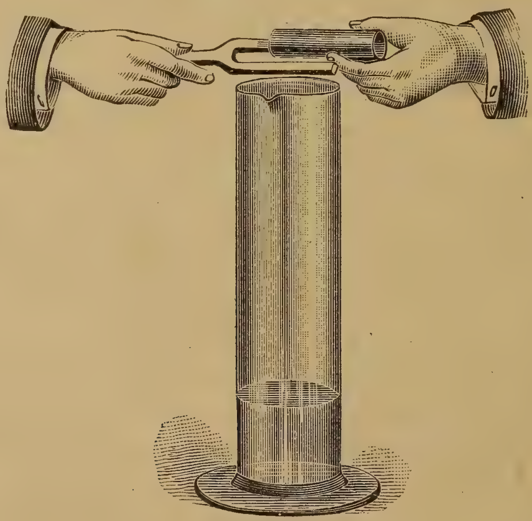


FIG. 19.

What is the effect upon the loudness of the sound?

The effects observed in the last experiment are explained by the fact that when the two prongs move towards each other a condensation is formed in the air between them, while rarefactions proceed from the backs of the prongs. The sound is, therefore, strong in the regions *d* and *f*, less intense at *c* and *e*, and disappears almost completely along the lines *gah* and *ibk* (Fig. 20), where the opposite pulses meet and neutralize each other.

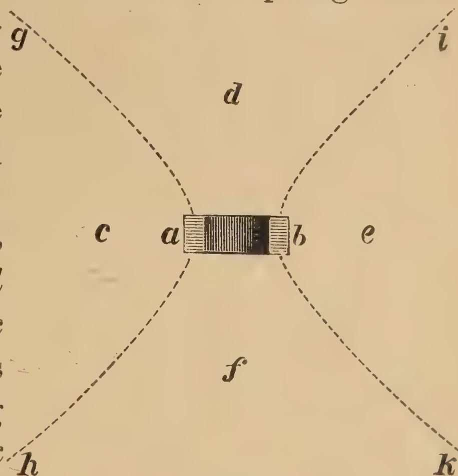


FIG. 20.

Experiment 2.

Take two brass U-tubes, A and B, connected by telescoping joints as shown in Fig. 21, short tubes being inserted at C and D. Adjust the tube A so that the distance from the opening C to the opening D will be the same around the tube in the direction CAD as in the direction CBD. Connect D with your ear by means of a piece of rubber tubing, and place a vibrating tuning-fork at the opening C.

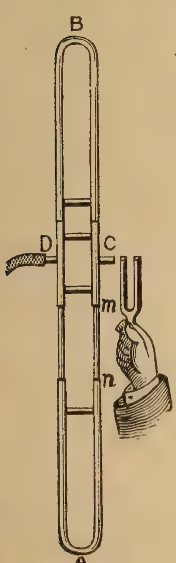


FIG. 21.

Note that the sound of the fork is heard, the sound-waves reaching the ear through both branches together.

Now draw A out until the intensity of the sound is a minimum.

If A is properly adjusted, the sound will almost, or altogether, disappear.

This will take place when the sound-waves passing through A reach the point D just one-half a wave-length behind those which leave C at the same time and pass through B. Pulses of rarefaction at D are always met by pulses of condensation, and the sound-waves are consequently destroyed.

In this case the distance around the tube in the direction CAD differs from the distance in the direction CBD by one-half a wave-length, that is, the distance mn is one-quarter of the length of the wave produced by the fork.

When two sound-waves interfere and thus destroy each other either wholly or partially, the effect is known as interference.

10. Determination of Wave-Length.

The instrument described in the experiment above may be used for determining the wave-length of the sound-wave produced by a tuning-fork.

The difference in the lengths of the paths CAD and CBD when complete interference takes place is one-half the wave-length of a sound-wave produced by the fork. That is, if m and n are together when the two paths are equal in length, the length of the sound-wave = 4 mn.

Experiment 3.

Determine the wave-lengths of the sound-waves produced by the different tuning-forks in your laboratory.

11. Determination of the Velocity of Sound in Air by Determination of Wave-Length.

The above furnishes an indirect method of determining the velocity of sound in air. If the vibration-number of the fork is known, and the wave-length determined, the velocity in air can be found from the relation

$$v = n\lambda. \qquad \text{(Art. 11, page 16.)}$$

From the determination of the wave-lengths of the sound-waves produced by the tuning-forks in Experiment 3, calculate the approximate speed of sound in the air.

12. Beats.

Experiment 4.

Take two tuning-forks of the same vibration number, hold one in each hand and make them sound together.

Note that the sounds blend perfectly.

Load one of the forks by sticking a piece of wax to the end of one of the prongs. Excite the forks and place each on its resonance-box.

Note that there is now no continuous flow of sound, but that the intensity is alternately increased and diminished.

This effect is the result of interference, and is called **beating.**

The loading of the fork causes it to vibrate more slowly and to originate sound-waves which are of greater wave-length than those produced by the other fork. Since the sound-waves proceeding from the forks are equal in

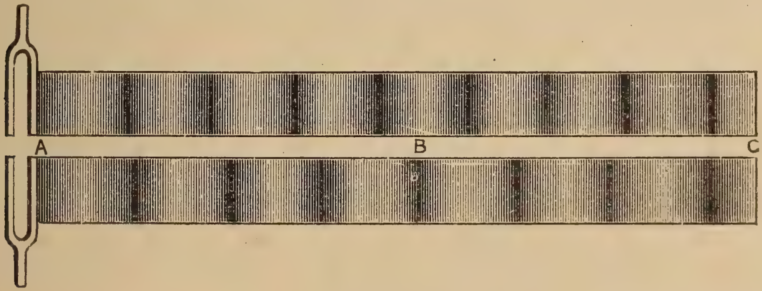


FIG. 22.

velocity and unequal in length, they periodically coincide, the condensation of the one with the condensation of the other (Fig. 22 A), or the rarefaction of the one

with rarefaction of the other (Fig. 22 C); and periodically interfere, the condensation of the one coinciding with the rarefaction of the other (Fig. 22 B). Thus alternate re-inforcements and diminutions of sound are produced.

QUESTIONS.

1. If a circular plate is made to vibrate in four sectors, as in Exp. 7, page 164, Part I., and if a cone-shaped funnel is connected with the ear by a rubber tube, and the other ear is stopped with soft wax, no sound is heard when the centre of the mouth of the cone is placed over the centre of the plate; but if it is moved outward along the middle of a vibrating sector, a sound is heard. Explain the reasons. Try the experiment. The mouth of the funnel should be about $2\frac{1}{2}$ inches in diameter, if the diameter of the plate is 6 inches.

2. A sounding tuning-fork, mounted on a resonance-box, is carried slowly toward the wall of a room. Why is it that the sound becomes wavy, rising and sinking at regular intervals?

3. A vibrating fork is placed before the opening C in the tubes (Fig. 21), and the observer at D notes that complete interference takes place when A is drawn out 13 inches. What is the length of the sound-wave which originates with the fork? If the vibration-number of the fork is 256, what is the velocity of sound in air?

4. A fork, whose vibration-number is 256, is made to vibrate before the opening C (Fig. 21), and perfect interference takes place when the tube A is drawn out 33 cm. What is the velocity of sound in the air?

5. When two tuning-forks are beating, show that the number of beats per second is always equal to the difference between the vibration-numbers of the forks.

CHAPTER III.

PITCH OF SOUNDS—MUSICAL SCALES.

1. Determination of the Pitch of a Note.

We have learned (page 175, Part I.) that the pitch of a musical note depends upon the rapidity of the vibrations which enter the ear. To determine the number of vibrations corresponding to any note, an instrument called a **siren** is used.

Fig. 23 shows the construction of a simple form of this instrument. C is a cylindrical air-chamber, upon the upper end of which is mounted a circular rotating disc B, which almost touches the upper surface of the cylinder. The disc is perforated at equal intervals along a circle near its circumference. The upper end of the air-chamber is also perforated, the holes corresponding in number, position, and size with those in the disc above. The holes in both the disc and the end of the chamber are drilled obliquely, those in the disc sloping in one direction and those in the end of the chamber in the opposite. The tube D at the lower end of the chamber is connected with a bellows or blower.

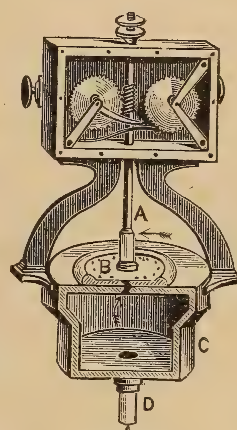


FIG. 23.

When air is forced into the chamber and passes up through the holes, the disc is made to rotate by the pressure of the air against the sides of the holes, the rapidity of rotation depending on the force with which the air is sent into the chamber.

As the disc rotates, vibrations will be set up in the external air by the puffs of air which pass out of the chamber when the holes in the disc are opposite those in the end of the chamber. A note will thus be produced, the pitch of which will depend on the rapidity with which the disc is rotated. By controlling the blower any note can be produced at will. Its number of vibrations per second can be determined by reading from the dial of a mechanical recorder attached to the spindle A, on which the disc is mounted, the number of revolutions made in any observed interval, multiplying this by the number of holes in the disc and dividing by the number of seconds in the interval.

Experiment 1.

If your laboratory is supplied with a siren, determine with it the number of vibrations per second of a tuning-fork. Excite the tuning-fork with a violin-bow, and at the same time press air through the siren, gradually increasing the speed of the rotating disc.

When distinct "beats," which indicate that the two notes are nearly alike in pitch, are heard, cautiously increase the speed until the beats disappear and the two notes blend. Now set the clockwork of the recorder in motion and keep the disc revolving at a uniform rate for an interval of time, say one-half minute. Read from the dial the number of revolutions, and calculate the vibration-frequency of the fork.

Experiment 2.

If the laboratory is not supplied with a siren, determine approximately the vibration-frequency of the tuning-fork in the following manner:—

Take a glass tube about 15 inches long and $\frac{3}{4}$ inches in diameter, and select a cork that will just slide up and down

within the tube, touching its sides. Attach a wire to the cork to serve as a handle. Insert the cork into one end of the tube, excite the fork and hold it over the other end of the tube. By means of the wire move the cork up or down until the position of the cork which causes the tube to give out its loudest sound is found. Now place the tube in a horizontal position in a support with its open end close to the disc used in Experiment 3, page 174, Part I., and facing the ring of holes (Fig. 24). Hold the tube through which the air is blown on the other side of the disc as shown in the figure, force air through the tube and turn the disc, gradually increasing or decreasing its speed until the velocity at which the tube gives out the loudest sound is found. Continue to revolve the disc at this rate for half a minute, and count the number of turns made by the handle in that time. Multiply the number of turns made by the handle by the number of times which the disc revolves for every turn of the handle, and this by the number

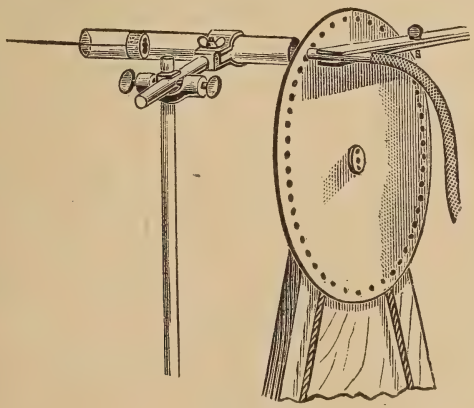


FIG. 24.

of holes in circle. Divide the product by 30, the number of seconds. The result will be the number of vibrations per second which the disc sends into the tube; but, since the tube is sounding its loudest, this is the number of vibrations made by the tuning-fork. The average of several results should be taken.

QUESTIONS.

1. When a sounding body approaches the ear, or recedes from it, the pitch of the tone appears to change. Explain the cause.

2. A person carries a vibrating tuning-fork. Will the pitch of the note appear the same to a person going before him as to a person following him, all three moving at the same rate? Give reasons for your answer.

3. If A carries a vibrating tuning-fork from B to C, will the pitch of the fork appear the same to A, B and C. If not, what will be the difference in their observations?

2. Musical Scales.

To produce an effect agreeable to the ear the notes cannot be used arbitrarily or at hazard. When once a note is chosen to begin a piece of music the notes which are to accompany or follow it must be selected according to well-defined laws.

In the music of all nations changes in pitch take place by definite intervals, and not by continuous transitions. Music, therefore, proceeds by notes clearly separated from one another.

A collection of notes whose vibration-numbers bear definite ratios to one another forms a **musical scale.**

The notes of a musical scale are selected according to this fundamental law. **Simultaneous or successive notes are agreeable to the ear only when their vibration-numbers bear simple ratios to one another.**

When the ratios are not simple, audible beats occur and dissonance results.

3. Harmonic Scale.

The harmonic scale is composed of a series of notes whose vibration-numbers are proportional to the natural numbers

$$1, 2, 3, 4, 5 \quad . \quad . \quad . \quad . \quad .$$

The first six at least of these form agreeable harmonies with the first.

The first is called the **fundamental** note, and the others when heard as auxiliaries to it are called **harmonics.**

The ratio between the vibration-number of one note and that of its antecedent note is called a **musical interval. The interval between two notes, therefore, is obtained by dividing the vibration-number of the one note by that of the other.**

Since the intervals between the notes are very great, music in which the notes used form a harmonic series is restricted and monotonous.

Following the principle that the less complicated the ratios of the vibration-numbers of the notes the more perfect the harmonies, physicists have constructed a natural scale in which the intervals are much smaller.

4. Diatonic Scale.

The interval between two notes whose vibration-numbers are in the ratio 1:2 is called an **octave.**

The sound produced by the simultaneous production of more than two separate notes is called a **chord.**

It is found that any three notes, X, Y, Z, whose vibration numbers are p, q, r respectively, are concordant if

$$p : q : r :: 4 : 5 : 6$$

Three such notes are called a **harmonic triad,** and if sounded with a fourth, which is the octave of the first, they form what is called a **major chord,** the most consonant chord found in music, the ratios of the vibration-numbers being the simplest possible.

The letters C, D, E, F, G, A, B, are used to denote notes connected in harmonic triads as follows:—

$$C : E : G :: 4 : 5 : 6$$
$$G : B : 2D :: 4 : 5 : 6$$
$$F : A : 2C :: 4 : 5 : 6.$$

Therefore,

The vibration-number of $E = \frac{5}{4}$ that of C.
" " $G = \frac{6}{4}$ or $\frac{3}{2}$ that of C.
" " $B = \frac{5}{4}$ that of $G = \frac{5}{4} \times \frac{3}{2}$ or $\frac{15}{8}$ that of C.
" " $D = \frac{3}{4}$ that of $G = \frac{3}{4} \times \frac{3}{2}$ or $\frac{9}{8}$ that of C.
" " $F = \frac{4}{3}$ that of C.
" " $A = \frac{5}{3}$ that of C.

Or,

the notes, C, D, E, F, G, A, B, C, have
the vibration-ratios 1, $\frac{9}{8}$, $\frac{5}{4}$, $\frac{4}{3}$, $\frac{3}{2}$, $\frac{5}{3}$, $\frac{15}{8}$, 2 and
the intervals $\frac{9}{8}$, $\frac{10}{9}$, $\frac{16}{15}$, $\frac{9}{8}$, $\frac{10}{9}$, $\frac{9}{8}$, $\frac{16}{15}$.

The above scale is called the **natural** or **diatonic** scale. The first, or lowest note, is called the **key-note,** and the last is taken as the key-note of another set of eight notes, and so on until a sufficiently extended scale is obtained.

5. Intervals of the Diatonic Scale.

An inspection of the scale shows that the intervals in this scale are not equal. Three are represented by $\frac{9}{8}$, two by $\frac{10}{9}$, and two by $\frac{16}{15}$. The intervals $\frac{9}{8}$, $\frac{10}{9}$ are known as **tones,** the first being a **major-tone** and the second a **minor-tone.** The interval $\frac{16}{15}$ is called a **major semi-tone.**

Other important intervals in the scale are the **major third** (C . . . E), the numerical value of which is $\frac{5}{4}$; the **fourth** (C . . . F), value, $\frac{4}{3}$; the **fifth** (C . . . G), value, $\frac{3}{2}$; and the **minor third** (A_1 . . . C_2), value, $\frac{6}{5}$.

6. Designation of Octaves.

The letters C, D, E, etc., distinguish the notes of an octave from one another. It is also necessary to have a means of designating the different octaves of any musical instrument. This is done in various ways. One of the best is to write the letter designating the note with a subscript figure which indicates the octave. For example, the C's of the eight octaves of the organ are written thus:—

$$C_{-2},\ C_{-1},\ C_1,\ C_2,\ C_3,\ C_4,\ C_5,\ C_6,\ C_7.$$

7. Standard of Pitch.

When once the vibration-number of any note is fixed, the vibration-ratios given above may be used to determine the vibration-numbers of the other notes. The pitch usually adopted by writers on acoustics and by makers of acoustical apparatus is $C_3 = 256$ double, or 512 single vibrations per second.

The vibration-number of the C's of the different octaves will then be

C_{-2},	C_{-1},	C_1,	C_2,	C_3,	C_4,	C_5,	C_6,	C_7.
16	32	64	128	256	512	1024	2048	4096

This pitch has the advantage of simplicity, the vibration-number of each C being a power of 2. The standard is a tuning-fork made to vibrate 256 times per second.

The international concert pitch adopted by musicians is $A_3 = 435$ double, or 870 single vibrations per second, and the standard is a tuning-fork made to vibrate 435 times per second.

1. Determine the vibration-number of each note in an octave when the vibration-number of A is 435.

2. What is the measure of the interval between the acoustic and the musical standard of pitch?

8. Transposition of Scales—Scale of Equal Temperament.

If C were always taken as the point of departure, the notes of the diatonic scale would be sufficient for all purposes except for minor chords; but since any note of the scale may be used as the key-note, it is obvious that to maintain the same succession of intervals, that is, $\frac{9}{8}$, $\frac{10}{9}$, $\frac{16}{15}$, etc., new and intermediate notes must be introduced. For example, comparing the scales tabulated below:—

	C_3,	D_3,	E_3,	F_3,	G_3,	A_3,	B_3,	C_4,	D_4,	E_4,	F_4,	G_4
Key of C....	256	288	320	$341\frac{1}{3}$	384	$426\frac{2}{3}$	480	512	576	640	$682\frac{2}{3}$	768
Key of G....	256	288	320	360	384	432	480	512	576	640	720	768,

it will be noted that the A's of the two scales differ by an interval of $\frac{80}{81}$ and the F's by an interval of $\frac{128}{135}$. Similarly every transition from one key to another adds extra tones. It has been calculated that with all the naturals as key-notes the scale would consist of at least 72 notes to the octave. Clearly it would be impracticable to construct instruments with fixed tones, like pianos or organs, to play in different keys. The difficulty is overcome by **tempering** the scale, that is, by reducing the number of notes by changing slightly the values of the intervals to equalize them. In the **scale of equal temperament** commonly adopted the octave is divided into twelve equal intervals, each of which is called a semi-tone, two intervals forming a tone. There are, therefore, twelve notes, and the pitch of each is obtained from the next lower by multiplying it by $\sqrt[12]{2}$; that is, the vibration-ratios of the notes in the octave are

$$1,\ 2^{\frac{1}{12}},\ 2^{\frac{2}{12}},\ 2^{\frac{3}{12}}\ \ .\ \ .\ \ .\ \ .\ \ 2$$

and each interval is $2^{\frac{1}{12}}$.

CHAPTER IV.

TRANSVERSE VIBRATIONS OF STRINGS.

1. Laws of Vibration.

We have learned, Art. 3, page 175, Part I., that the vibration-frequency of a stretched string or wire depends on its length, its diameter, its tension and its density. Let us examine the subject more closely to determine the exact laws of vibration.

Experiment 1.

Stretch two piano wires A and B on a sonometer, tune them in unison, and place a movable bridge under the centre of B. Pluck wire A at its centre and B at the centre of one of its halves. Compare the notes. It will be found that the note given by the short wire is just one octave above that given by the wire vibrating as a whole.

1. How does the vibration-number of a note given by a wire compare with the vibration-number of the note given by the same wire when its length is decreased by one-half?

Repeat the experiment, shortening B with the movable bridge successively to $\frac{8}{9}$, $\frac{4}{5}$, $\frac{3}{4}$, $\frac{2}{3}$, $\frac{3}{5}$, and $\frac{8}{15}$ of its length.

2. What will be the successive intervals between the notes emitted by wires A and B?

3. What then is the relation between the length of a wire and the number of vibrations which it makes per second.

Experiment 2.

Place a wire B on a sonometer, let it pass over the pulley and hang a weight from its end. Tune another wire A in unison with it. Note the weight that is hung from B

and add other weights until it vibrates in unison with (1) one-half of A, (2) one-third of A, (3) one-fourth of A, etc. It will be found that the weight is in (1) 4 times, in (2) 9 times, in (3) 16 times the original weight.

1. How does the number of vibrations per second made by the wire B when it vibrates in unison with (1) $\frac{1}{2}$ A, (2) $\frac{1}{3}$ A, (3) $\frac{1}{4}$ A compare with the number of vibrations made by the same wire when it vibrates in unison with A ?

2. What caused the difference ?

3. What then is the relation between the tension of the wire and the number of vibrations which it makes per second ?

Experiment 3.

Measure with a micrometer caliper the diameters of several wires B, C, D, E, etc., and stretch them successively by the same weight on a sonometer. Tune a wire A to vibrate in unison with the largest wire, say B, and, using a movable bridge, determine what fraction of A's length will vibrate in unison with each of the other wires. It will be found that the ratio of the length will be inversely as that of the diameters.

Experiment 4.

Stretch with equal tension on the sonometer a steel wire and a brass one of the same diameter. Place a movable bridge under each, adjust the bridges until lengths of the wires are found which vibrate in unison, and measure these lengths. It will be found that the length of the steel wire is to the length of the brass wire as the square root of the density of the steel is the square root of the density of the brass; but the vibration-numbers of wires are inversely proportional to their lengths, therefore their vibration-numbers are inversely proportional to the square roots of their densities.

The same is found to be true of wires of other materials.

The above experiments, and others of a more general character, carefully performed, verify the following laws:

1. When the tension is constant the number of vibrations per second varies inversely as the length.

2. The number of vibrations per second varies as the square root of the tension.

3. The number of vibrations per second varies inversely as the diameter.

4. The number of vibrations per second varies inversely as the square root of the density of the material of which the string is composed.

QUESTIONS.

1. What are the proportionate lengths of a stretched string which gives, when vibrating, a harmonic series of notes?

2. Stretch a wire on the sonometer, and, taking the note which it gives when it vibrates as a whole as a fundamental note, shift the movable bridge to the proper position to produce in order the other notes of a harmonic series.

3. What are the proportionate lengths of a stretched string which gives the notes of the diatonic scale?

4. Stretch a wire on a sonometer, and tune it to vibrate as a whole in unison with a C-fork. Determine the positions where the movable bridge must be placed to give each of the other notes in the octave. Place the bridge in the proper positions and produce the notes.

5. A wire stretched on a sonometer by hanging a weight W from one of its ends gives the note C. What weights must be hung in succession from its end that the string may give in order the notes of the diatonic scale?

6. A string stretched on a sonometer gives a certain note. What must be the diameters of wires of the same material and the same length that will, when stretched to the same tension, give notes which will be in a harmonic series with the first?

7. A and B are two wires of the same material and thickness. A is two feet long, and is stretched by a weight of $8\frac{1}{2}$ pounds. B is

four feet long, and is stretched by a weight of 34 pounds. How are the notes which the wires yield when struck related to each other?

8. A steel wire one yard long, and stretched by a weight of 5 pounds, vibrates 100 times per second when plucked. What must be the tension of two yards of the same wire that it may vibrate twice as fast?

9. Two precisely similar strings A and B have the same tension. If the tension of A is doubled, and the length of B is halved, how must the tension of B be altered to give the same note as A?

10. Two similar wires of the same length are stretched, the one by a weight of 4 pounds and the other by a weight of 9 pounds. What is the interval between the notes which they produce?

11. A stretched string 3 feet long gives the note C when vibrating transversely. What note will be given by a string one-quarter the thickness and one foot long, made of the same material and stretched by the same weight?

12. Four exactly similar strings, stretched with the same tension, are vibrating side by side. How will the note emitted be affected if they are fastened together so as to form one string, by winding around them an extremely thin piece of silk?

13. A silver and an iron wire of the same diameter are stretched by weights of 4 and 36 pounds respectively. When plucked they give the same note. If the density of silver is 10.5, and that of iron 7.8, find the relative lengths of the wires.

CHAPTER V.

VIBRATION OF AIR IN TUBES.

I.—Resonance.

Experiment 1.

Repeat Experiment 5, page 180, Part I.

The cause of the phenomena observed in this experiment can be best understood by performing some simple experiments with the wave machine used in Experiment 3, page 5.

Experiment 2.

Fix the left-hand end of the spiral by pushing a cork into it and fastening the cork in an immovable clamp. Take hold of the right-hand end, and, by pushing it in, send a pulse of condensation along the spiral. Watch it as it is reflected from the fixed end, and the instant it reaches the free end pull the coil outward, producing a pulse of rarefaction, When this is reflected and returns to the free end, push the coil inward, and so on until the spiral vibrates as a whole steadily. You will then observe :

1. That at the fixed end the coils are alternately crowded together and then drawn apart.

2. That the amplitude of vibration of the coils at the free end is greater than at any other part of the spiral, but that they remain at about the same distance apart.

3. That to form a complete wave of condensation and rarefaction, a pulse of condensation travels from the free end to the fixed end, and back again to the free end ; and is then followed by a pulse of

rarefaction, which also travels from the free end to the fixed end, and is reflected back to the free end.

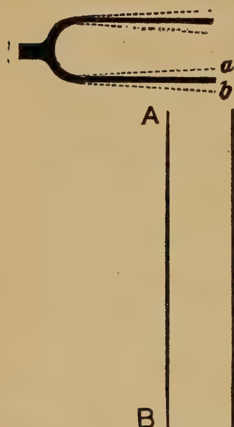


Fig. 25.

The wave-length is therefore four times the length of the spiral.

The motion of the coil spring furnishes an illustration of the manner in which the air-column in the tube is believed to vibrate.

The movement of a prong of the fork in the direction *a* to *b* (Fig. 25) produces in the air a pulse of condensation, which runs down to the bottom of the jar and is reflected back. Now, if the distance AB is such that this pulse of condensation reaches the prong of the fork at the instant that it is on the point of returning from *b* to *a*, a pulse of rarefaction will be produced, which will run to the bottom of the jar and back, and, overtaking the prong when it reaches its limit *a*, will again be changed by it to a pulse of condensation.

The vibrations of the tuning-fork will therefore be re-inforced by synchronous vibrations of the air-column in the tube, and the intensity of the sound thus increased.

It is evident that the distance AB must be just one-quarter of the wave-length of the wave produced by the fork, and since the wave-length depends upon the vibration-frequency of the fork, the distance AB must vary with different forks.

Since there can be no gain in energy, the increase in the intensity of the note when a resonator is used must be accompanied by a decrease in the length of time during which it sounds

1. Resonators.

Resonators are used for analyzing composite sounds. Fig. 26 shows two common forms of the instrument. They are made in various sizes, and each is carefully tuned to a definite pitch. The small opening *a* is placed in the ear, and if the sound to which the resonator is tuned exist in the air, it is re-inforced by the vibration of the air within the cavity, and its presence is thus made known to the observer. By applying successively different resonators to the ear, the simple notes which make up a composite tone may be determined.

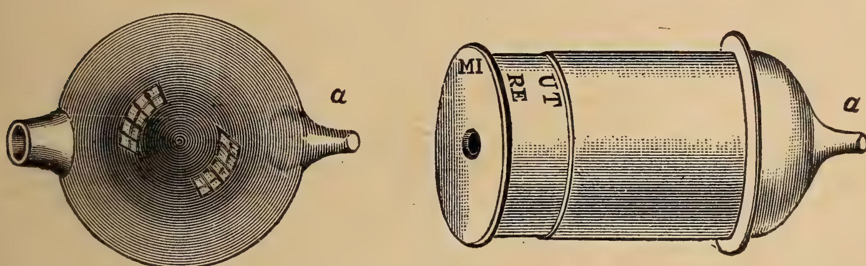


FIG. 26.

2. Determination of the Velocity of Sound by Resonance.

Since AB (Fig. 25) is just one-quarter the wave-length of the sound-wave produced by the fork, the wave-length is known when AB is measured; and if the vibration-number of the fork is known, the velocity of sound in air can be calculated from the equation

$$v = n\lambda \qquad \text{(Art. 11, page 16.)}$$

The velocity in other gases may be determined in the same way.

II.—Vibration of Air in Tubes.

3. Vibration of Air in Closed Tubes.

Experiment 1.

Take a glass tube, about 30 inches long and three quarters of an inch in diameter, insert by means of a stiff wire a cork which will slide up and down in the tube, just touching the sides (Fig. 27). Adjust the cork so that the air within the upper end of the tube will vibrate in unison with a tuning-fork. With a piece of brass tubing flattened at one end, blow across the end of the tube.

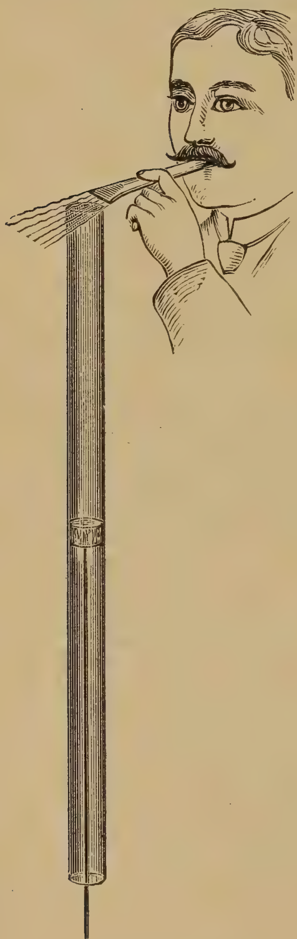


Fig. 27.

1. How does the note produced compare with that given when the fork is placed above it?

2. The blowing across the mouth of the tube causes a mixture of vibrations of different frequencies. Why is it that the tube causes one note to become dominant?

Experiment 2.

Adjust the cork in the tube used in the last experiment so that the air-column will be 24 inches in length. Blow across the end of the tube. Repeat the experiment, making the length of the air-column (*a*) 12 inches, (*b*) 6 inches.

1. What is the relation between the vibration-numbers of the notes given by (1) the 24-inch and the 12-inch air-columns, (2) the 12-inch and the 6-inch air-columns?

2. Determine by trial the different lengths of the tube necessary to give the notes of the diatonic scale.

When a flutter, caused by the co-mingling of a number of vibrations of different frequencies, is made at the

mouth of a tube, the air-column within the tube selects the vibrations which are in synchronism with itself, vibrates in unison with them, and re-inforces them, thus producing a musical note.

The vibration-number of the note produced by a vibrating air-column within a tube varies inversely as the length of the tube.

4. Vibration of Air in Open Pipes.

Experiment 3.

Blow a puff of air across the end of a glass tube open at both ends. Now close one end and blow a puff of air across the open end.

How does the pitch of the note in the first case compare with that in the second case ?

Experiment 4.

Select two glass tubes of the same bore, one of which is twice the length of the other, close one end of the short tube, and blow a puff of air across an open end of each.

What is the relation between the vibration-numbers of the notes produced by the two pipes ?

A tube open at both ends gives a note whose vibration-number is double that given by a tube of the same length which is closed at one end.

A tube closed at one end will, therefore, give the same note as an open one of twice the length; but the wave-length of the sound-wave is four times the length of a stopped tube, **therefore the length of the open tube is one-half the wave-length of the sound-wave produced by it.**

The vibration of the air in an open tube may also be illustrated by a coil-spring wave-machine.

Experiment 5.

Push both ends inward at once, thus sending two pulses of condensation towards the centre. Watch them as they cross

in the centre, and when they reach the ends, pull both ends outwards. Repeat this process until the two halves of the coil vibrate steadily in and out. Now observe :—

1. That when a pulse reaches the end of the spiral its type is changed, and if it is a pulse of condensation it is reflected as a pulse of rarefaction, and *vice versa.*

2. That the centre remains stationary.

3. That the condensations and the rarefactions are not uniformly distributed along the spiral, but are greatest at the centre and least at the ends.

4. That at the ends where the coils remain always about the same distance apart the amplitude of vibration is the greatest.

5. That the rate of vibration is twice as great as when one end of the spiral was fixed (Exp. 2, page 45). What is the reason?

Fig. 28.

The air-column in the open tube is believed to vibrate in much the same way as the coil-spring was made to vibrate in the last experiment.

The movement of the prong of the fork in the direction a to b (Fig. 28) produces in the air a pulse of condensation, which runs down to the end of the jar. Its type is then changed, and it is reflected back as a pulse of rarefaction. When it reaches the upper end, its type is again changed, and it is reflected as a pulse of condensation. Now if the distance AB is such that the prong of the fork is just starting to move again from a to b at the instant that this pulse of condensation starts down the tube, the vibration of the fork will be re-inforced by the vibration of the air-column. This evidently can take place only when the distance AB is one-half the wave-length of the note.

5. Nodes and Loops in Pipes.

Since the layer of air at the closed end of a stopped pipe is necessarily at rest, and since rapid alternations of condensation and rarefaction take place there, the density of the air at this point, like the relative positions of the coils at the fixed end of the spiral (Exp. 2, page 45), is constantly changing.

At the open end of a tube the air has a constant density, that of the atmosphere; consequently the air particles, like the coils at the free end of the coil-spring, remain at about the same distance apart. The amplitude of the vibration of the air particles at this point is, therefore, at a maximum.

A node in an air-column of a pipe is a section of the column where the particles of air are at rest, but where the changes of density are the greatest.

A loop is a section of the air-column where the vibrations of the particles of air have the greatest amplitudes, but where there is no change of density.

In a stopped pipe there is a loop at the open end and a node at the closed end. In an open pipe there is a loop at each end, and a node at the centre.

The existence of nodes and loops may be shown experimentally by placing a light powder in a horizontal tube (Exp. 9, page 165, Part I). When a note is sounded the powder accumulates at the points of rest. Their existence may also be shown as in Experiment 6, page 52.

6. Organ Pipes.

Fig. 29 shows the construction of a common organ pipe. Air is forced through the tube T

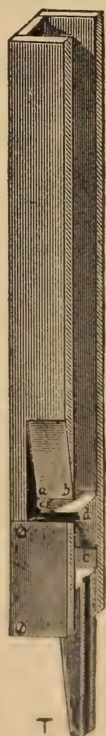


FIG. 29.

into the chamber C. The compressed air escapes from this chamber by a narrow slit *ed*, and, striking against the narrow bevelled edge, or lip *ab*, produces a fluttering noise. The vibrations of the flutter which are in synchronism with the air-column of the tube are re-inforced by it, and a musical note, the pitch of which depends upon the length of the tube, results.

Fig. 30.

7. To Show the Existence of Nodes and Loops in an Organ Pipe.

Experiment 6.

Make a small tambourine by stretching a membrane over a circular hoop. Scatter fine sand on the membrane and by means of a string lower it slowly into an organ pipe which is producing a musical note (Fig. 30). Observe the sand.

What evidence have you of the existence of loops and nodes?

Repeat the experiment several times, varying the force of the current of air passing through the tube.

Is there a node at the centre of the tube in each case? Are there other nodes? If so, where?

8. Overtones of Pipes.

Repeat the experiments on nodes and loops in strings, Part I., pages 181, 182.

Experiment 7.

Blow a strong blast across the end of the tube used in experiment 2, page 34.

Note the overtones which mingle with the fundamental note emitted by the pipe.

When a pipe is blown gently it yields its fundamental note. By gradually increasing the force of the current of air the air-column is made to break up into vibrating segments, and hence to yield overtones.

Upon what does the **quality** of the note emitted by a pipe depend? See Part I., page 182.

The series of overtones given by a stopped pipe differs from that given by an open one, as will be seen from a consideration of the following conditions:—

(1) There must be a loop at the open end of a tube, and a node at the closed end.

(2) Nodes and loops recur alternately.

On these conditions the following will be the simplest possible divisions of air-columns in pipes.

9. In Stopped Pipes.

The open end remains always a loop and the closed end a node (Fig. 31). If there are no other nodes and loops, the pipe yields its fundamental note only.

FIG. 31.

FIG. 32.

FIG. 33.

FIG. 34.

FIG. 35.

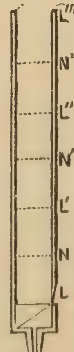


FIG. 36.

When the pressure of the air is increased, the air-column divides into three equal parts, and an additional

node and loop are formed (Fig. 32). If the air pressure is still increased, the air-column divides into 5, 7, 9, etc., equal parts (Fig. 33). Hence the vibration-numbers of the possible notes given by a stopped pipe are in the proportion 1, 3, 5, etc., and **odd harmonics only are, therefore, present in the overtones of a stopped pipe.**

10. In Open Pipes.

A loop remains always at each end of the pipe. When the fundamental note is sounded there is but one node, that at the centre (Fig. 34).

When the first overtone is produced there will be a loop at the centre, and the air-column divides as shown in Fig. 35.

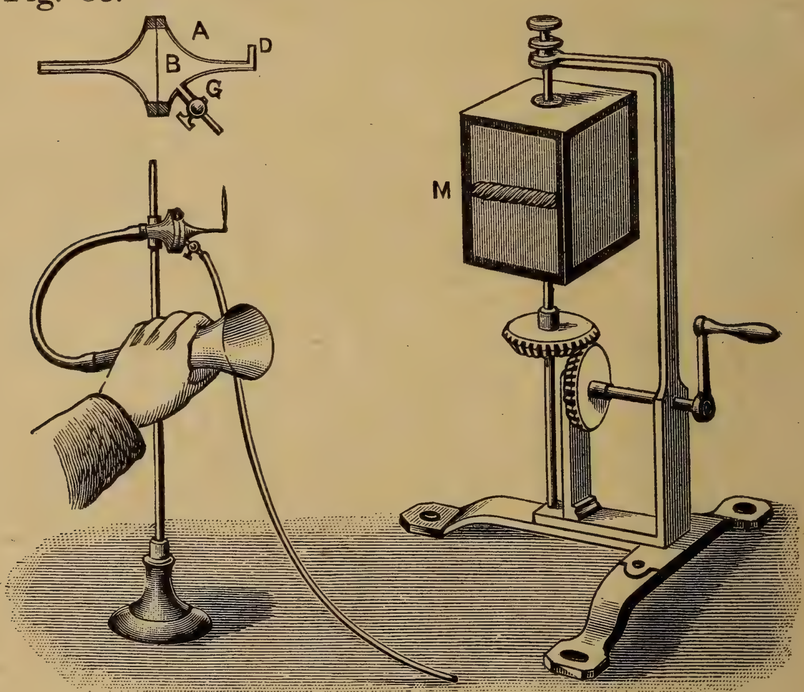


Fig. 37.

When the second overtone is produced the column will divide as shown in Fig. 36. The other overtones are

formed by similar divisions. Hence the vibration-numbers of the possible notes given by an open pipe are in the proportion, 1, 2, 3, 4, etc., and, therefore, **the overtones together with the fundamental note form a complete harmonic series.**

The **quality** of the musical sounds given by the pipes will depend upon **the degree of complexity of the vibration of the air-columns** (Art. 10, page 182, Part I).

11. Manometric Flames.

Koenig has devised a means of showing the complex nature of sound-vibrations by means of a vibrating gas flame. Fig. 37 shows the construction of the apparatus. A box or capsule A is divided into two compartments by a thin membrane B. Gas is admitted into one of the compartments by a tap G, and is lit at the nozzle D. The other compartment is connected by means of a rubber tube with a funnel-shaped mouth-piece. A rotating mirror is placed in front of the gas flame. When sound-waves enter the capsule by the mouth-piece, the membrane, gas and flame are set in vibration. By revolving the mirror the image is drawn out into a band of light. If the flame is burning steadily, the band will be continuous; but if the flame is vibrating, it will have a

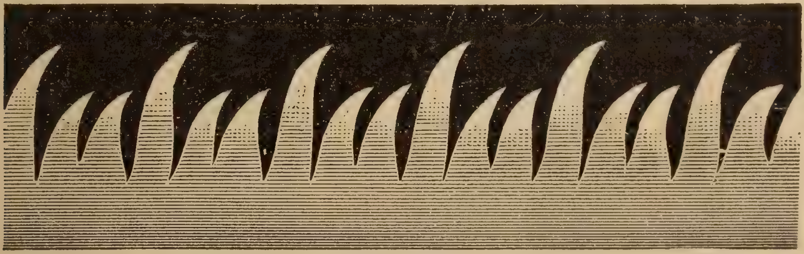


FIG. 38.

wavy appearance. The complexity of the vibrations is shown by the succession of images which appear on the mirror (Fig. 38).

Fig. 39 shows the image when the vowel E is sung in front of the mouth-piece on the note C.

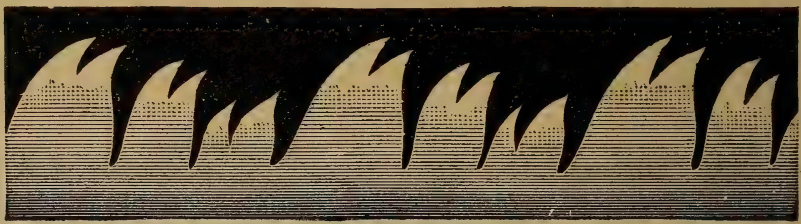


Fig. 39.

Experiment 8.

Revolve the mirror and sing into the mouth-piece the vowel A (1) on the note F, (2) on the note C.

Make a drawing of the image made by the flame in each case.

Vary the experiment by singing different vowel sounds on different notes, by blowing a toy trumpet and by making sounds of various kinds in front of the mouth-piece.

Instead of connecting the capsule with the mouth-piece, it may be connected with organ pipes, resonators, etc., and the character of the vibrations of air-columns

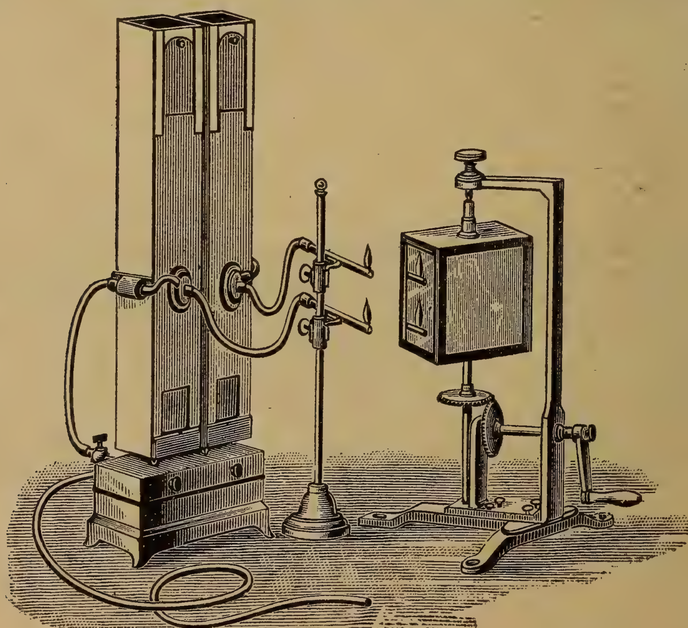


Fig. 40.

observed. Fig. 40 shows a method of comparing the vibrations of two air-columns in organ pipes.

Let two different persons repeat in succession the above experiments.

Are the images alike? If not, explain the reason.

QUESTIONS.

1. Calculate the depth of a resonant jar for a fork whose vibration-number is 440, when the velocity of sound in air is 1,100 feet per sec.

2. It is found that the depth of a resonant jar which gives the loudest sound with a fork whose vibration-number is 256 is 13.2 inches. What is the velocity of sound in air?

3. A tuning-fork, making 384 vibrations per second, is held over a cylindrical jar in which the velocity of sound is 1,100 feet per second. What must be the length of the jar in order that it may be best adapted to resound to the fork? What is the length of the wave sent out by the fork?

4. When a tuning-fork is set in vibration, and held close to one end of a glass tube 20 inches long and open at both ends, an augmentation of sound takes place. If the tube is longer or shorter than 20 inches, the increase of sound is not so great. How do you explain these facts, and how could you calculate from them the pitch of the tuning-fork?

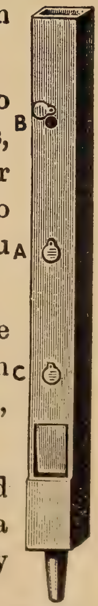


FIG. 41.

5. A stopped organ pipe 4 feet long, and an open organ pipe 12 feet long, are sounded. How are the notes related to each other? Do they differ from each other in quality, and, if so, why?

6. Give the lengths of the three shortest closed tubes, and of the three shortest open tubes, which will resound to a tuning-fork making 200 vibrations per second, the velocity of sound being 33,240 cm. per second.

7. If a pipe is constructed with holes bored in one of its sides, and these covered with little doors, as shown in Fig. 41,

what effect will be produced on the vibrations of the air-column within the tube by opening A, B, and C in succession?

8. What effect is produced by the opening and the closing with the fingers of the lateral orifices of a flute? Explain.

9. A stopped pipe 2 feet long and an open pipe 4 feet long give the same fundamental notes. How do these two notes differ in quality?

CHAPTER VI.

NATURE AND PROPAGATION OF LIGHT.

1. Theory of the Nature and Propagation of Light.

Before proceeding with this chapter, the student should repeat the experiments described in Chapter XXI., Part I., and make himself familiar with the theory of the nature and propagation of light.

2. Sources of Light for the Laboratory.

For most experiments in light, it is necessary to darken the laboratory. Close wooden shutters, either hinged or supported by weights and made to slide up and down, are the best, but blinds made of the cloth used by carriage makers for covering buggy tops answer well. If blinds are used, they should be mounted on spring rollers, and the light should be shut out at the edges by having the blinds run in grooves not less than 6 inches deep.

It is convenient to have some ready means of controlling and directing fairly powerful beams and pencils of light for experimental purposes.

If the sun is the source of light, a porte lumiere is used to transmit the light into the laboratory. This consists of a mirror A, which can be so adjusted that direct sunlight is reflected through the tubular opening B (Fig. 42). A double-convex lens should be mounted in a brass ring made to slip easily into the tube B. This lens is called the condenser. A lantern objective C

should be supported in front of the condenser on a metal bar D, which can be quickly adjusted or removed.

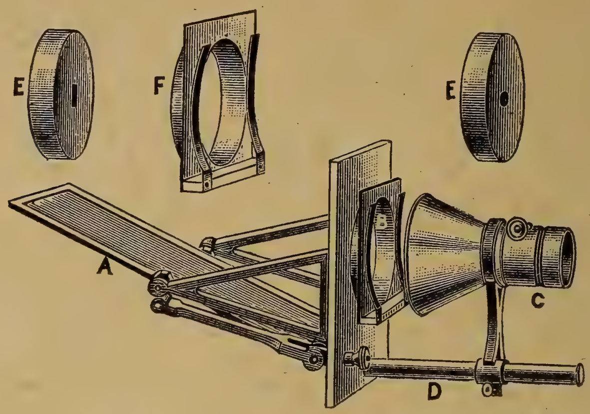


FIG. 42.

Caps E, E, with circular openings and slits, are made to fit over the tube B.

A slide-holder F, which also can be attached to the tube B, as shown in the figure, should be provided.

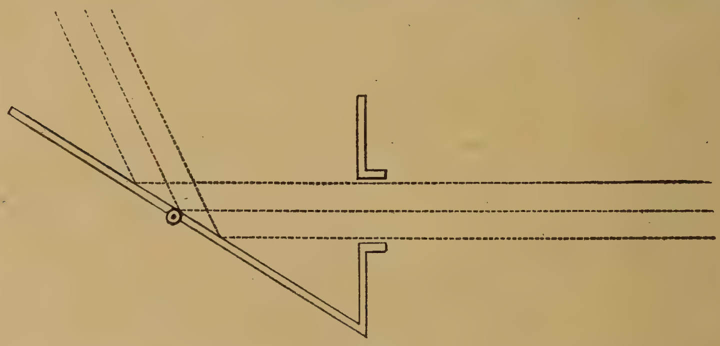


FIG. 43.

To introduce a beam of light into the laboratory, attach the porte lumiere to a shutter in a window facing south, remove all the lenses and adjust the mirror (Fig. 43). The size of the beam may be regulated by using caps with apertures of various sizes.

To introduce a convergent or a divergent pencil, slide the condensing lens into the tube (Fig. 44). The pencil will be convergent to a focus, and divergent beyond the focus.

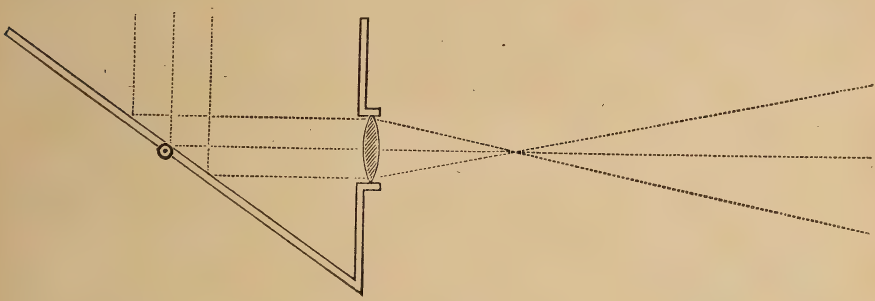


FIG. 44.

To project lantern slides, place the condensing lens and the objective in position, attach the slide-holder to the tube, place the slide in position, and move the objective backward or forward until the picture is focused on

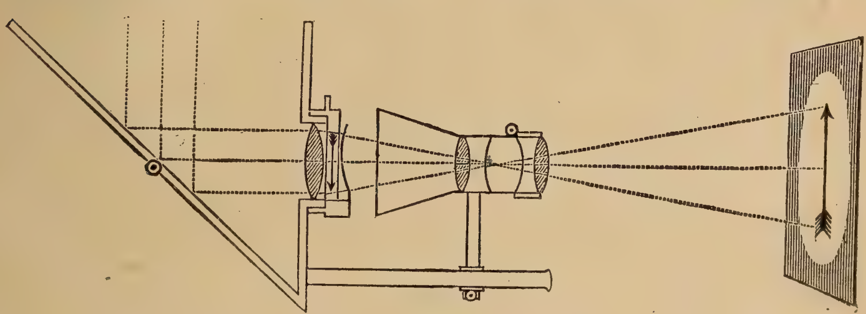


FIG. 45.

a white screen placed in front of the objective (Fig. 45). A plaster wall makes the best screen. Pieces of apparatus, and experiments that can be performed on a small scale, may also be projected in the same manner by placing the apparatus between the condenser and the objective. If it is not convenient to use a lantern

objective, an ordinary double-convex lens mounted on a stand may be used for this purpose.

If the sun is not used as the source of light, a box for shutting in the radiant must be provided. The apparatus then becomes a projection lantern. The simplest form of the lantern is that which most nearly resembles

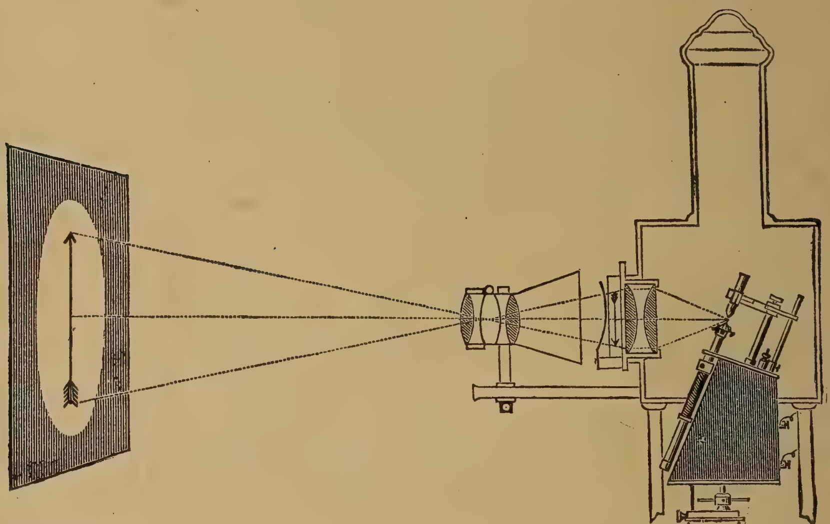


FIG. 46.

the porte lumiere described above. The tube for holding the condensing lens, the objective, the support, the caps, the slide-holder, etc., are the same. The lantern differs from the porte lumiere simply in substituting a ventilated box to enclose the radiant for the adjustable mirror which reflects the sunlight. Fig. 46 shows a projection lantern with an electric arc lamp as the source of light. This is the best radiant for experimental purposes; but an oxy-hydrogen lamp, an acetylene gas flame or a good coal-oil lamp will give sufficient light if the room is well darkened and the screen is not placed at too great a distance. The ordinary closed front lanterns, sold for projecting slides alone, are not adapted for physical work.

To obtain a beam of light with the lantern, remove the objective, place a single plano-convex lens in the

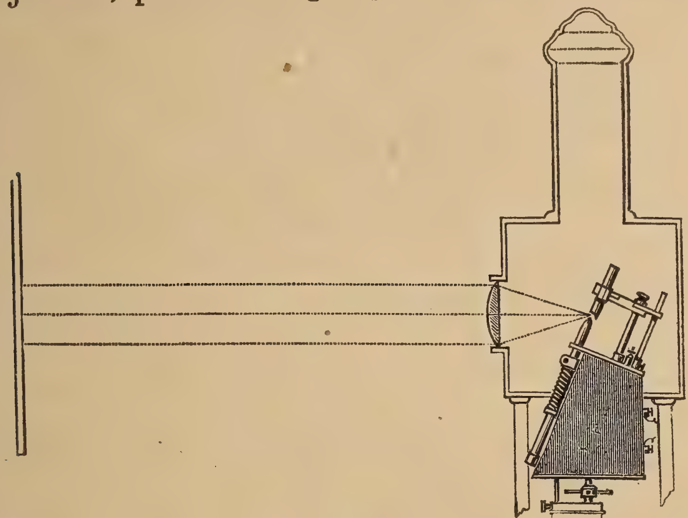


FIG. 47.

tube, and draw the radiant back until the light becomes parallel (Fig. 47).

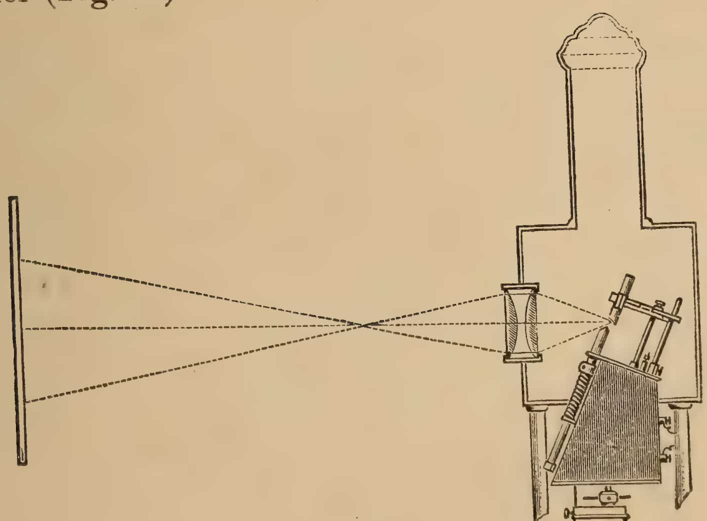


FIG. 48.

To obtain a convergent or a divergent pencil, place two plano-convex lenses in the tube (Fig. 48).

To project slides, place the two plano-convex lenses in the tube, rest the slide in position, and focus on the screen with the objective (Fig. 46).

3. Rectilinear Propagation of Light.

Repeat Experiment 2, page 253, Part I.

Experiment 1.

By means of a porte lumiere or projection lantern introduce a beam of light into a darkened room, and burn some touch-paper in its path.

1. What evidence have you that light travels in straight lines.

2. Is it the light which is made visible to you by the burning of the paper?

4. Images by Means of Small Apertures.

Repeat Experiment 4, page 254, Part I.

Experiment 2.

Remove all the lenses from the porte lumiere, or projection lantern, cover the front with a sheet of tin-foil, and prick a pin-hole in it.

A round image of the sun, or an inverted image of the lantern radiant appears on the screen. Make several pin-holes near the first. Observe the number of the images increasing and overlapping as the pin-holes are made. The more the tin-foil is removed by pricking holes in it, the more the images overlap and become confused.

Remove the tin-foil altogether. The light on the screen may be regarded as the overlapping of an infinite number of images of the radiant.

Why is it that a single image is produced only by a very small aperture?

5. Shadows.

Repeat Experiments 6 and 7, page 256, Part I.

Experiment 3.

Place a blackened ball three or four inches in diameter at various positions in the path of the light between a porte lumiere or lantern and a screen, when the light is (*a*) divergent, (*b*) parallel, (*c*) convergent.

Make diagrams to show (*a*) the characters of the umbral and penumbral cones, (*b*) the distribution of light and shade on the screen, for the different positions.

CHAPTER VII.

PHOTOMETRY.

1. Illuminating Power.

Since light is a form of energy it is a measurable quantity. It is a matter of common observation that the quantity of light given out by one luminous body may differ widely from that given out by another. A candle, for example, gives out less light than a coal-oil lamp, and a coal-oil lamp much less than an electric arc lamp. The **illuminating power of a source of light is usually measured by a unit quantity, which is the light given out by a candle of a certain weight burning at a certain rate.** The illuminating power is then measured in candle-powers.

2. Intensity of Illumination.

The **illuminating power** of a source of light must not be confounded with the **intensity of the illumination** which it produces. A candle and a coal-oil lamp, although differing in illuminating power, or the quantity of light given out by them, may illuminate the same surface to the same extent, if their distances from the surface be different.

The intensity of illumination on a given surface is the quantity of light received on a unit surface.

This is manifestly dependent on :—

1. The illuminating power of the source of light, the intensity of illumination being directly proportional to illuminating power.

2. The distance of the surface from the source of light.

Since light, like sound, travels outward in waves in every direction from its source, it is inferred by reasoning similar to that of Art. 3, page 20, that **the intensity of illumination on a given surface is inversely as the square of its distance from the source of light.**

This law may be illustrated by the following experiment :—

Experiment 1.

Remove the condensers and the objective from a projection lantern, and slip over the tube a cap in which there is a small square aperture, say 1 in. square. Place a screen successively at distances of 1 ft., 2 ft., 3 ft., etc., from the radiant, measure the side of the square of light projected on the screen at each of these distances, and calculate the areas of these squares. It will be found that they are approximately in the proportion 1, 4, 9, etc., that is, 1^2, 2^2, 3^2, etc. ; but the quantity of light falling on the screen is the same in each case, therefore the light falling on a unit surface, or the intensity of the illumination, is in the proportion 1, $\frac{1}{2^2}$, $\frac{1}{3^2}$, etc. The surface of the radiant should be as small as possible.

3. Measurement of Illuminating Power.

Since the illuminating power of any source of light is directly proportional to the intensity of the illumination which it produces on a surface when the distance is constant, and the intensity of the illumination of a surface varies inversely as the square of the distance from the source of light, the relative illuminating powers of different sources of light may be determined by comparing the intensities of the illuminations produced at known distances. All common photometers, or instruments for comparing the illuminating powers of different

sources of light, depend on the application of these principles.

4. Rumford's Shadow Photometer.

Count Rumford devised a means of comparing the illuminating powers of two sources of light by a comparison of shadows. The following experiment explains his method.

Experiment 2.

To compare the illuminating powers of a coal-oil lamp and a candle, place a small upright rod in front of a screen

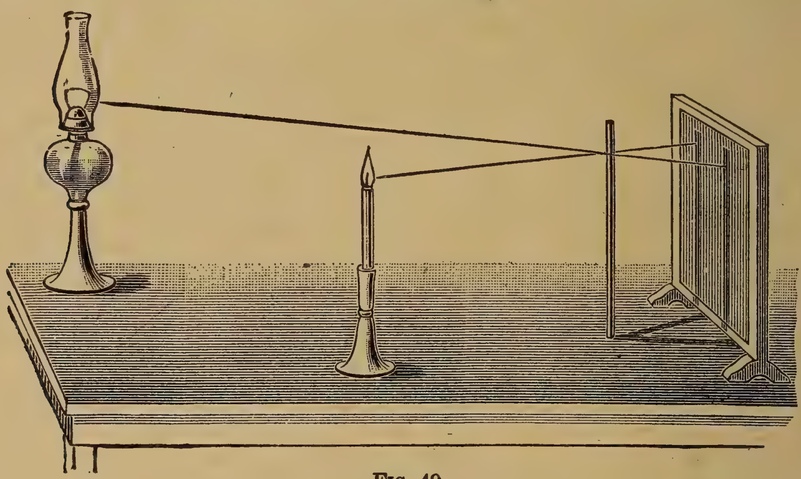


FIG. 49.

made of a sheet of white paper, as shown in Fig. 49, and place the candle so that a shadow is cast by the rod on the screen when the room is darkened. Now place the lamp in such a position that another shadow of equal depth, or degree of darkness, is cast by the rod alongside the first. Measure the distance (D_1) from the candle to the screen, and the distance (D_2) from the lamp to the screen.

$$D_1 = ?$$
$$D_2 = ?$$

The part of the surface of the screen on which the candle shadow falls is illuminated by the lamp only, and the part of the surface on which the lamp shadow falls is illuminated by the candle only, and the shadows are of equal depth; hence the intensity of illumination produced by the candle when at a distance D_1 equals the intensity of the illumination produced by the lamp at a distance D_2.

If I_1 and I_2 denote the illuminating powers of the candle and the lamp respectively, I_1 and I_2 will be proportional to the intensities of the illuminations produced by the candle and by the lamp respectively at a unit distance.

When I_1 is the intensity of illumination produced by the candle at a unit distance,

$\frac{I_1}{D_1^2}$ = the intensity of illumination at a distance of D_1;
(Law of Inverse Squares),

and when I_2 is the intensity of illumination produced by the lamp at a unit distance,

$\frac{I_2}{D_2^2}$ = the intensity of the illumination of the lamp at a distance D_2. But the intensity of the illumination produced by candle at the distance D_1 = the intensity of illumination produced by the lamp at a distance D_2.

That is,

$$\frac{I_1}{D_1^2} = \frac{I_2}{D_2^2}$$

or,

$$\frac{I_2}{I_1} = \frac{D_2^2}{D_1^2} = ?$$

If the candle is a standard candle, the illuminating power of the lamp

$$= \frac{D_2^2}{D_1^2} \text{ candle-power.}$$

5. Bunsen's Grease-Spot Photometer.

It will be observed that if a grease-spot is made on a sheet of white paper, and a light placed on one side of the paper, it will appear light on a dark ground to a person on the side of the paper opposite to the light, but dark on a light ground to a person who views it from the side on which the light is situated. If the two sides are equally illuminated, the spot becomes almost invisible. The photometer introduced by Bunsen is an application of this principle.

Experiment 3.

To compare the illuminating power of a lamp flame with that of a candle by Bunsen's photometer.

Drop a little melted paraffin on a sheet of unsized paper (thin drawing paper answers well), and after it has become hardened remove the excess of paraffin with a knife; place the paper between two pieces of blotting-paper, and run over the blotting paper a moderately hot iron, thus making a grease-spot on the paper about 2 or 3 centimetres in diameter. Cut out of the paper a circular disc 10 or 12 centimetres in diameter, with the spot at its centre. Mount this disc in a suitable frame attached to a support.

Now draw a chalk line on a table and lay off alongside of it a centimetre scale. Place the candle at one end, and the lamp at the other; and between them place the disc with the centre of the grease-spot at the same height as each of the flames (Fig. 50). Move the disc backward or forward along the line until the position is found where the grease-spot becomes as nearly as possible invisible. The two sides of the disc are then equally illuminated. Measure the distance (D_1) of the candle from the disc, and the distance (D_2) of the lamp from the disc.

$$D_1 = ?$$
$$D_2 = ?$$

Let I_1 and I_2 denote the illuminating powers of the candle and the lamp respectively. Then, by reasoning similar to that in Art. 4 above,

$$\frac{I^2}{I_1} = \frac{D_2^2}{D_1^2} = ?$$

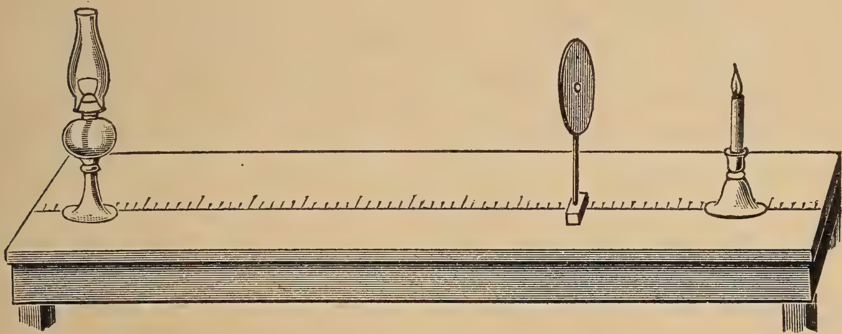


Fig. 50.

For convenience in determining whether the two sides of the disc are equally illuminated, a V-shaped mirror is sometimes mounted, as shown in Fig. 55, in such a position that images of the spot from opposite sides may be seen in it and compared.

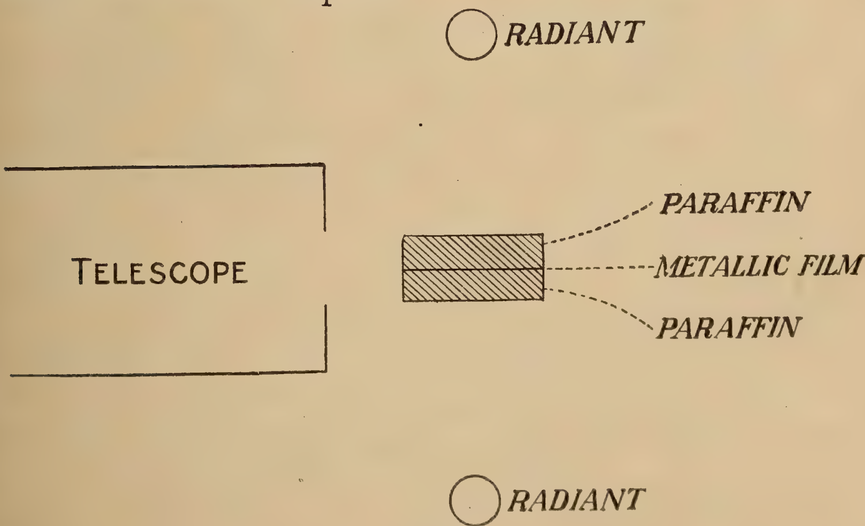


Fig. 51.

A screen made by enclosing a bright metallic reflecting film between two thin rectangular slabs of paraffin, as shown in Fig. 51, is now frequently used instead of the

disc with the grease spot at its centre. It is so placed within a blackened box, having circular openings in the ends, that the opposite sides of the metallic film are illuminated by the radiants to be compared. The reflected light from the surfaces illuminate the paraffin slabs, and any differences in the degree of illumination is readily detected by an observer looking at edge of the screen through a telescope inserted in the side of the box opposite it, as shown in Fig. 52.

In an instrument constructed for accurate determinations, the disc, candles and supports for lights to be tested, are mounted on holders which slide on a graduated bar. The same bar may be made to carry

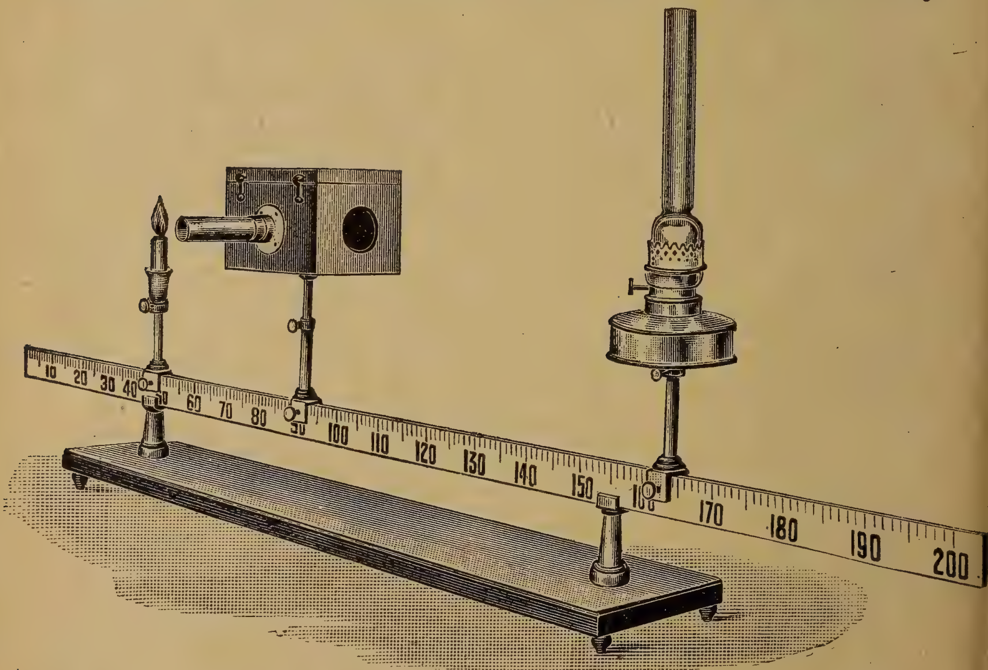


FIG. 52.

lenses, mirrors, etc., for other optical experiments. The instrument is then called an **optical bench.**

Simple forms of the optical bench are shown in Figs. 52 and 53. In Fig. 53 the sliding pieces are wooden blocks fitted into a wooden trough, one side of which is graduated. The uprights in Fig. 52 are attached to brass sliders carried upon a graduated wooden strip. Figs. 52 and 54 show these different forms of the bridge fitted as photometers, one carrying the grease spot disc, and the other the paraffin screen attachment.

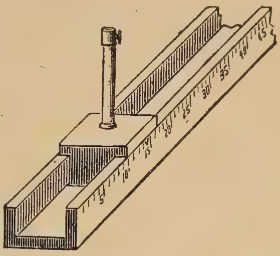


FIG. 53.

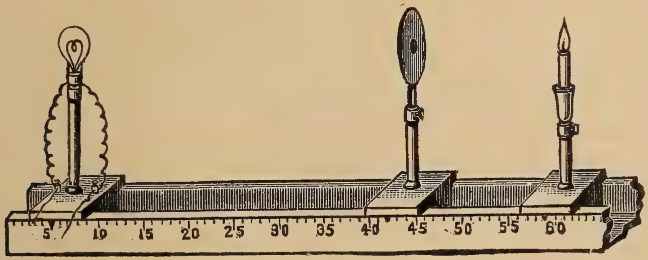


FIG. 54.

6. How May a Bunsen's Photometer be Used to Prove the Law of Inverse Squares?

Experiment 4.

Support a candle on a sliding piece of an optical bench and four similar candles in a line at right angles to the bench on another piece, placing the screen on a sliding piece between them, as shown in Fig. 55.

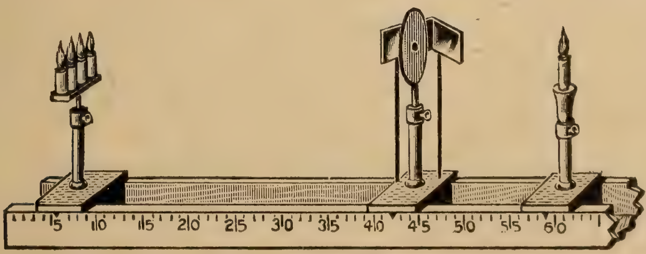


FIG. 55.

Light the candles, and trim the wicks so that the flames shall be as nearly as possible equal in size.

Place the middle of the line of four flames at distances of (*a*) 80 cm., (*b*) 100 cm., (*c*) 120 cm. from the screen, and in each case adjust the sliding piece carrying the single candle to cause the grease-spot to disappear.

What is the distance of the candle flame from the screen in each case?

QUESTIONS.

1. A candle is placed at a distance of 2 feet from a screen, and then removed to a distance of 3 feet. Compare the intensities of illumination of the screen in the two cases.

2. A candle is placed at a distance of 10 inches from a screen and a lamp of 10 candle-power is placed on the other side of the screen at a distance of 10 feet from it. Compare the intensities of illumination on the two sides of the screen.

3. In a Rumford's photometer, it is found that the shadows are of equal depth when one of the lights is at a distance of 110 cm. from the screen, and the other at a distance of 200 cm. from it. Compare the illuminating powers of the lights.

4. How can you make use of a Bunsen photometer to prove the law of inverse squares?

5. In measuring the illuminating powers of an incandescent lamp with a Bunsen photometer, it is found that the distance from the disc to a standard candle is 25 centimetres, and the distance from the disc to the lamp 100 cm. What is the candle-power of the lamp?

6. A standard candle and a gas-flame of 4 candle-power are placed 6 feet apart. Where would a Bunsen disc have to be placed between them to cause the grease-spot to disappear?

CHAPTER VIII.

REFLECTION OF LIGHT.

1. Laws of Reflection.

Repeat the experiments described in Part I. which lead up to the determination of the laws of reflection. See pages 260–262, Part I.

Experiment 1.

Arrange apparatus as shown in Fig. 56. The mirror is mounted so that it can rotate on an axis. The protractor is attached to the mirror, and stands at right angles to its plane, the line drawn from the axis of the mirror to the zero of the protractor being a normal to the mirror. Place the mirror so that a very small beam of light from a porte lumiere or lantern will be close to the protractor, parallel to its plane, and fall upon the mirror at its axis. Burn touch-paper in the path of the beam of light, and by turning the mirror on its axis make it take different positions. Read on the graduated arc of the protractor the angles which the incident and the reflected beams make with the normal for each position of the mirror.

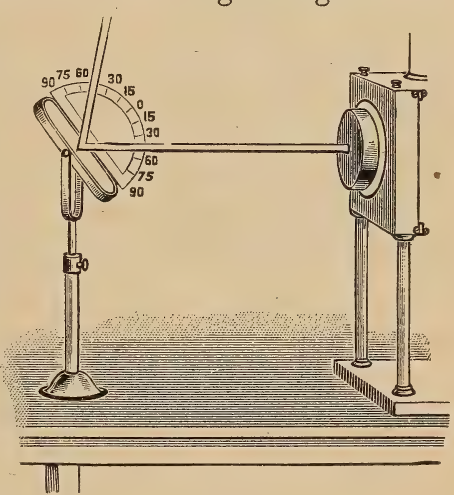


FIG. 56.

1. Are these angles always equal as the mirror is rotated?

2. The incident beam was made parallel to the plane of the protractor. Is the reflected beam also in the same plane?

2. Geometrical Construction to Find the Image of a Point Formed by a Plane Mirror.

We have determined experimentally (Experiment 5, page 264, Part I.), that **the image of a point formed by a plane mirror is behind the mirror at a distance equal to that of the point from the mirror, and on the perpendicular let fall from this point on the mirror.**

This proposition follows directly from the laws of reflection of light.

The rays of light from any luminous point A in front of a mirror MN (Fig. 57) proceed from A in all directions, and any ray AB incident upon the mirror is reflected by it in the direction BE, the angle of incidence ABD being equal to the angle of reflection DBE; and, to an observer whose eye is in the line BE, the light will appear to come from a point behind the mirror in the line EB produced.

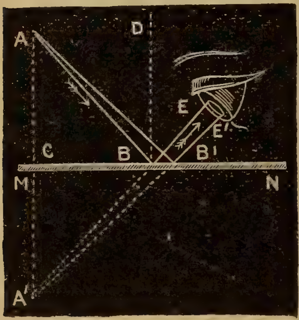


FIG. 57.

If a perpendicular AC is drawn to the mirror and produced to meet EB produced in A_1, the triangle ABC will equal the triangle A_1BC, because the side CB is common to the two triangles, and the angle

$$ACB = 90° = A_1CB,$$

also the angle

$$\begin{aligned} ABC &= 90° - ABD \\ &= 90° - DBE \\ &= EBN = A_1BC, \end{aligned}$$

therefore the triangles are equal in all respects.

Hence

$$AC = A_1C.$$

In the same way it is shown that any other ray AB_1 incident on the mirror and reflected by it along a line B_1E_1 according to the laws of reflection, will appear to proceed from the point A_1 which is in the line E_1B_1 produced.

Hence all the rays from A which fall upon the mirror appear to diverge from the point A_1. It is, therefore, the **image** of the point.

3. Virtual and Real Images.

It is manifest that the rays **only appear** to diverge from the point A_1, but the eye is affected in the same way as if the rays really did diverge from this point, and an image is seen. The image has no real existence, because the rays do not come from the other side of the mirror.

When the rays from a luminous point are so reflected, or changed, that they appear to diverge from a point, this point is called a virtual image; but when the rays of a luminous point are so reflected, or changed, that they really diverge again from some other point, this point is called a real image.

4. Image of a Luminous Object Formed by a Plane Mirror.

The image of a luminous object is made up of the images of the infinite number of luminous points which compose it; but when the positions of the images of a limited number of these points are found, the form and the position of the image of the object can usually be determined.

For example, when the positions of the images of the points A and B of the object AB (Fig. 58) are determined by the method given in Art. 2 above, the position of the image A_1B_1 is determined.

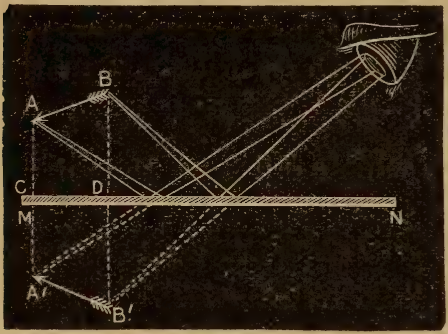


FIG. 58.

A study of this figure shows that **the image of the object formed by a plane mirror is virtual, erect, and of the same size and shape as the object, and is situated as far behind the mirror as the object is in front of it.**

5. Multiple Images in Inclined Mirrors.

Experiment 2.

Take two pieces of mirror glass, each 15 cm. square, and join two of their edges by pasting a strip of cloth on their backs to serve as a hinge. Set them up vertically on a sheet

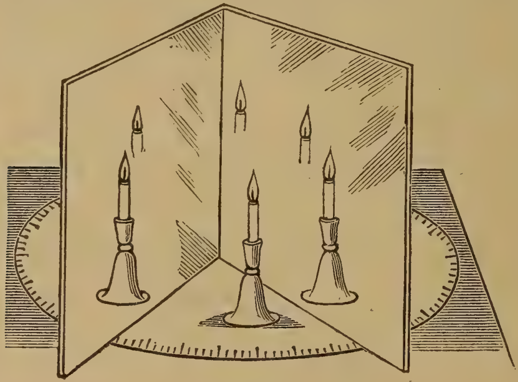


FIG. 59.

of paper on which is drawn a circle graduated in degrees, the axis of the mirrors being placed in line with the centre of the circle (Fig. 59). Place a lighted candle between the mirrors, and observe the number of images formed.

1. How many images are formed when the mirrors make an angle of 90° with each other? How many when the angle is 60°? How many when 30°?

2. Show by changing the positions of the mirror, and counting the number of the images formed that, if θ denotes the angle between the mirrors, and n denotes the number of images,

$$n = \frac{360}{\theta} - 1$$

when θ is an aliquot part of 360.

The formation of the images is due to the repeated reflections of the light from one mirror to the other, and each mirror gives rise to a separate series of images. The positions of the images are determined by the law that the image of a point is behind the mirror at a distance equal to that of the point from the mirror, and on the perpendicular let fall from this point on the mirror.

When the first image of the point in each mirror is determined, it is regarded as a virtual object; and its image in the other mirror is determined in the same way as if it were a real object placed at this point. This second virtual image is regarded as a virtual object, and so on. The process is repeated as long as any one of the images is situated in front of the plane in which a mirror stands.

For example, it is required to find the position of all the images of a luminous point A formed by two plane mirrors OM and ON, which make an angle of 60° with each other (Fig. 60).

Draw the line AB, at right angles to OM, and produce it to A_1, making $AB = A_1B$.

Then A_1 is the position of the first of the series of images originating with the mirror OM.

Draw a line AC, at right angles to ON, and produce it to A_2, making $AC = A_2C$.

Then A_2 is the position of the first of the series of images originating with the mirror ON.

Now regard A_1 and A_2 as virtual objects, and find A_3, the image of A_1 in the mirror ON, by drawing A_1A_3 at right angles to ON, making $A_1B_1 = A_3B_1$; and also find A_4, the image of A_2 in the mirror OM, by drawing A_2A_4 at right angles to MO produced, making $A_2B_2 = A_4B_2$.

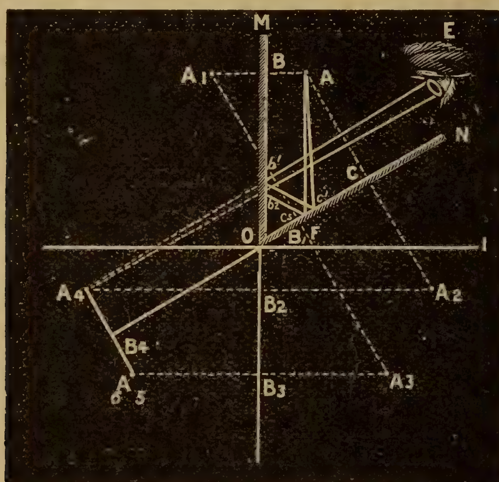


FIG. 60.

In the same way, find A_5, the image of A_3 formed by the mirror OM, and A_6, the image of A_4 formed by the mirror ON; but these images are coincident. A_5 or A_6 is behind the plane of each mirror, and no additional image is formed.

The figure also shows how to trace the rays by which any image, for example A_4, is seen by an eye placed in any position E in front of the mirrors. The light which appears to diverge from the image is in reality reflected from the surface b_1b_2 of the mirror OM, upon which it

is incident from the surface $c_1 c_2$ of the mirror ON, upon which, in turn, it is incident from the luminous point A. The lines representing the rays are so drawn that the angle of incidence in each case equals the angle of reflection, $b_1 c_1$ and $b_2 c_2$, if produced, intersecting in A_2.

6. Multiple Images in Parallel Mirrors.

Experiment 3.

Place two mirrors vertically on a table parallel with, and facing each other, and place a lighted candle between them. Now look obliquely into one mirror just over the edge of the other.

1. How do you account for the large number of images seen?

2. What limit is there to the number formed?

3. Why do they appear at equal distances in the same straight line? To answer this question draw the rays by which any three successive images are seen.

Experiment 4.

Hold a lighted candle before a mirror made of thick glass, and observe the images.

1. How many images are seen?

2. Explain the reason that more than one image is formed.

QUESTIONS.

1. Show that when the mirror (Fig. 56) is turned on its axis, the reflected beam describes an angle which is twice as great as that described by the mirror.

2. Explain by aid of a diagram how a person can see a complete image of himself in a plane mirror one-half his height.

3. A candle stands in front of a mirror which is inclined to the vertical at an angle of 30°. Show by a diagram the position of the image, and the path of the rays by which an observer sees the two ends of the candle.

4. A person stood beside a muddy lake with the sun behind him, and his shadow was thrown distinctly on the water. He afterwards stood beside a clear deep lake with the sun likewise behind him, and saw no shadow. Explain these observations.

5. On a moonlight night when the surface of the sea is covered with small ripples, instead of an image of the moon being seen in the sea, a long band of light is observed on its surface, extending toward the point which is vertically beneath the moon. Explain this phenomenon by aid of a diagram.

6. Show by a diagram how it is possible for a lady by the use of two mirrors to see an image of the back of her head.

7. A ray of light is successively reflected from two mirrors inclined at right angles to each other. What is the relative position of the first incident ray and the last reflected one?

8. Find, by construction, the number of images formed of a luminous point by two plane mirrors inclined to each other at an angle of 40° (*a*) when the point is on the bisector of the angle (*b*) when it is to one side of the bisector.

9. A person is equidistant from two plane mirrors which meet in the corner of a square room. In what way does the image of himself which he sees when looking toward the corner of the room differ from the image which he sees when looking toward one side of the room?

10. A ray of light is incident on one mirror in a direction parallel to a second, and after reflection at the second retraces its own course. What was the angle between the mirrors? If the ray after reflection from the second had been parallel to the first, what would have been the angle between the mirrors?

III.—Concave and Convex Spherical Mirrors.

7. To Determine How a Concave Mirror Disposes of Incident Light.

Experiment 1.

Cause a beam of light from a porte lumiere or lantern to be incident perpendicularly on a concave mirror, and burn some touch-paper in front of the mirror.

1. How does the mirror dispose of the light incident upon it?

The action of the mirror follows directly from the laws of reflection of light (Art. 1, page 75). But before proceeding to consider this question it will be necessary to explain some of the terms applied to concave and convex mirrors. A spherical mirror MN (Fig. 61) is a very small segment of a spherical surface. It is described as **concave** or **convex**, according as the reflection takes place from the internal or the external surface. The **centre of curvature** C, is the centre of the sphere of which the mirror is the segment.

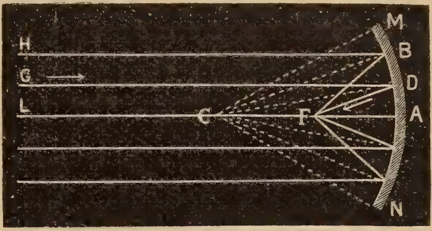


FIG. 61.

The **centre of figure** A, is the centre of the mirror itself.

An **axis** is any line passing through the centre of curvature and incident upon the mirror. The **principal axis** CA, is a line passing through the centre of curvature, and the centre of figure. Other axes are called **secondary**.

The **radius of curvature** is any line passing from the centre of curvature to the mirror.

To explain the phenomenon observed in Experiment 1 above, imagine the surface of the spherical mirror to be made up of an infinite number of infinitely small plane surfaces. A normal to each of these will pass through the centre of curvature.

Hence any axis of the mirror is a normal to its surface.

When a ray H, parallel with the principal axis is incident upon the mirror at B, it is reflected, and, the angle of incidence HBC being equal to the angle of

reflection CBF, the reflected ray cuts the principal axis in F (Fig. 61).

When the segment MN is small as compared with the surface of the sphere, and the beam of light not large, all other rays, G, L, etc., parallel with H and the principal axis, are reflected in the same way and brought practically to the same point F. This point F is called the **principal focus** of the mirror, and the distance AF is called the **principal focal distance.**

8. Position of Principal Focus.

An incident ray HB, parallel with the principal axis, is reflected and passes through the focus F (Fig. 62).

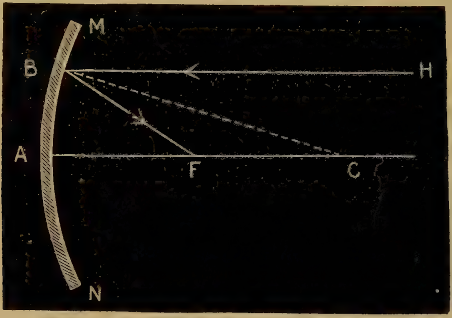


FIG. 62.

The angle FBC = the angle HBC
= the angle FCB;
therefore, FB = FC.

When AB is very small, FB is approximately equal to FA; therefore

$$AF = FC = \tfrac{1}{2}\,AC, \text{ approximately.}$$

Hence

The principal focal distance for rays incident on a small portion of the surface of a spherical mirror surrounding the centre of figure equals half the radius of curvature of the mirror.

9. To Find Experimentally the Principal Focus, and Hence the Centre of Curvature of a Concave Mirror.

Experiment 2.

Mount the mirror on a sliding piece of an optical bench (Fig. 63), and cause a small beam of light from a lantern or

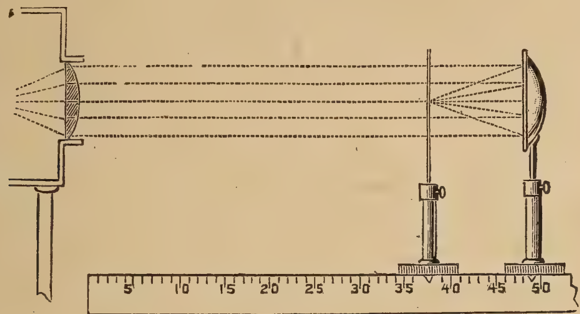


Fig. 63.

porte lumiere to be incident perpendicularly upon the mirror; attach a vertical wire to another sliding piece placed in front of the mirror, burn touch-paper in the path of the light, and move the wire up to the point where the rays are brought to a focus. Observe the distance on the scale between the wire and the centre of figure of the mirror.

1. What is the principal focal distance of the mirror?

2. What, therefore, is the radius of curvature of the mirror? Make a record of these numbers. They will be required in some of the experiments which follow.

10. To Locate Experimentally the Position of the Focus for Light Diverging from a Centre and Incident upon a Concave Mirror.

Experiment 3.

Arrange apparatus as in the last experiment. Place in the path of the beam of light near the tube of the lantern or porte lumiere a lens, the focal distance of which is about 30 or

40 cm. (Fig. 64), and attach the mirror to another sliding piece placed a distance beyond the focus of the lens. The light which is incident on the mirror will be divergent.

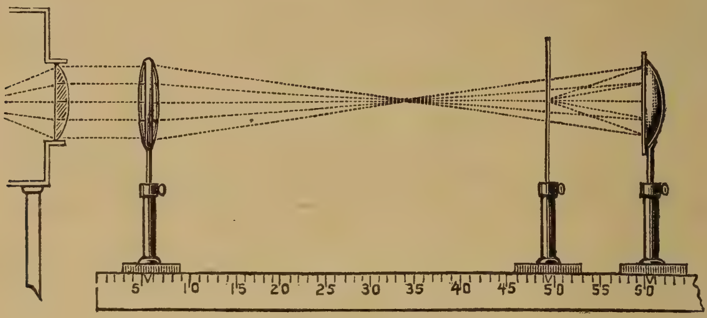


FIG. 64.

Burn touch-paper, and gradually move the mirror up toward the focus of the lens. Mark the foci with wires, as in Experiment 2.

1. Where is the focus of the reflected rays when the light diverges from (1) a point beyond the centre of curvature of the mirror, (2) the centre of curvature, (3) a point between the centre of curvature and the principal focus, (4) the principal focus, (5) a point between the principal focus and the mirror? Bring the mirror up between the lens and its focus—that is, let convergent light fall upon it. What is the course of the light after reflection?

11. Conjugate Foci.

Can the point from which light diverges and the focus to which it is brought by reflection be interchanged? Try.

Two points so related that the light diverging from either is brought by reflection from a mirror to a focus at the other, are called the conjugate foci of the mirror.

Repeat Experiment 3 above and show that if u and v are respectively the distances AP and AQ (Fig. 65) of the con-

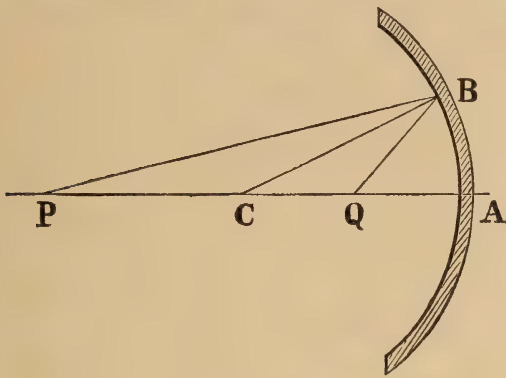


FIG. 65.

jugate foci from the centre of figure, and r is the radius of curvature of the mirror

$$\frac{1}{u} + \frac{1}{v} = \frac{2}{r} \text{ approximately.}[1]$$

12. To Determine How a Convex Mirror Disposes of Incident Light.

Experiment 4.

Repeat Experiments 2 and 3 above, using a convex mirror instead of a concave one.

1. What changes in the direction of the rays take place by reflection when a convex mirror is placed in the path of (1) a beam of light, (2) in a divergent pencil, (3) in a convergent pencil.

---

[1] This proposition may be demonstrated geometrically as follows:—

Since BC bisects the angle PBQ,

$$\frac{PB}{BQ} = \frac{PC}{CQ}.$$

But when AB is very small PB = PA and QB = QA approximately.

Hence, $$\frac{u}{v} = \frac{u - r}{r - v}$$

or $$\frac{1}{u} + \frac{1}{v} = \frac{2}{r}.$$

IV.—Images Formed by Concave and Convex Mirrors.

13. To Determine Experimentally the Character of the Images Formed by a Concave Mirror.

Experiment 1.

Support the concave mirror at one end of the optical bench and place a lighted candle on a sliding piece at a distance

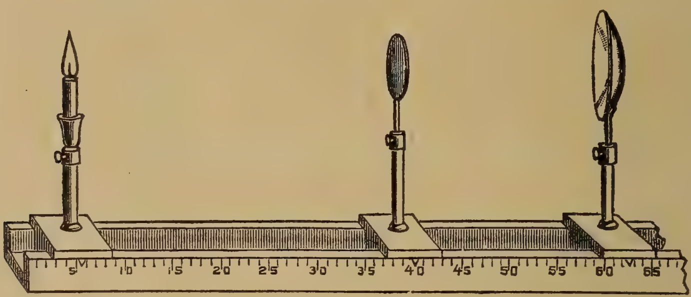


FIG. 66.

greater than the centre of curvature from the mirror. Support on another sliding piece a small paper or ground glass screen, placed between the candle and the mirror (Fig. 66). Slide the screen backward or forward until a sharply defined image of the candle is formed on it.

1. Is the image real or virtual? How do you know?

2. Is it larger or smaller than the candle?

3. Is the image erect or inverted?

4. At what point with respect to the centre of curvature and the principal focus is the image found?

Move the candle gradually toward the mirror, adjusting the screen to receive the image.

1. What change takes place in the position and the size of the image?

2. Where is the image when the candle is at the centre of curvature? Explain.

3. Where is the image when the candle is between the centre of curvature and the principal focus? What are its characteristics?

4. Where is the image when the candle is at the principal focus? Explain.

5. Where is the image when the candle is between the principal focus and the mirror? To answer this question look in the mirror. What are the characteristics of the image?

The above experiments show that in concave mirrors:—

(1) **The image of an object placed beyond the centre of curvature is real, inverted, smaller than the object, and placed between the centre of curvature and the principal focus.**

(2) **The image of an object placed between the centre of curvature and the principal focus is real, inverted, larger than the object, and placed beyond the centre of curvature.**

(3) **The image of an object placed between the principal focus and the mirror is virtual, erect, larger than the object, and placed back of the mirror.**

(4) **The image of a luminous point placed at the centre of curvature of the mirror is coincident with the point, because the rays of light from the object return to it after reflection.**

(5) **No image of a luminous point placed at the focus is formed because the rays of light from it after reflection become parallel with the principal axis, and consequently are not brought again to a focus and an image formed.**

1. How can number (4) above be used to determine experimentally the centre of curvature of a concave mirror?

2. Does the formula

$$\frac{1}{u} + \frac{1}{v} = \frac{2}{r}$$

which gives the relation of the distances of a luminous point and its image from the mirror, hold approximately for the candle and its image?

To answer this question repeat Experiment 1, placing the candle beyond the centre of curvature, and moving

it by stages towards the mirror. Adjust the screen to receive the image, and measure the distances u of the candle and v of the image from the mirror for each position of the candle. Tabulate the results as follows:—

u	$\frac{1}{u}$	v	$\frac{1}{v}$	Value of $\frac{1}{u}+\frac{1}{v}=\frac{2}{r}$	Value of r

Compare the results recorded in the last column with the value of r determined in Experiment 2 page 85.

How may the formula

$$\frac{1}{u}+\frac{1}{v}=\frac{2}{r}$$

be made use of for determining experimentally the radius of curvature or the principal focal length of a mirror?

14. To Determine Experimentally the Character of the Image Formed by a Convex Mirror.

Experiment 2.

Place a lighted candle at different points in front of a convex mirror. Look into the mirror for the image. It will be seen that the **image is always virtual, erect, smaller than the object, and placed back of the mirror.**

15. Drawing of Images Formed by Mirrors.

In locating by a geometrical construction the points which determine the form and the position of an image, the following principles should be observed :—

1. The image of a luminous point is located where any two rays after reflection intersect.

2. The rays of which the direction after reflection can usually most easily be determined are: (*a*) a ray parallel with the principal axis, and (*b*) a ray passing in the direction of the centre of curvature. The first is reflected through the principal focus, and the second returns along the same line.

To locate the image of any luminous point, therefore, draw from the point a line parallel to the principal axis of the mirror, and from the point where this line meets the mirror draw a line through the principal focus. The image of the point will be in this line. Again, draw from the luminous point a line through the centre of curvature and produce it to meet the mirror. Since the light is reflected back along this line, the image will be in it also. Hence the image will be located at the point where these two lines intersect.

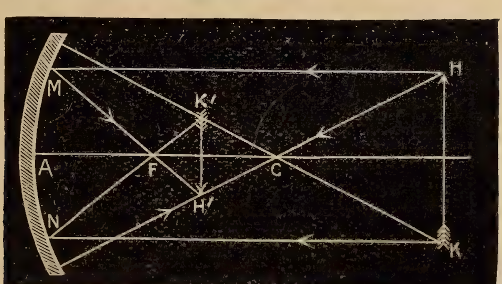


Fig. 67.

Fig. 67 shows the position and the character of the image H_1K_1 of an object HK placed beyond the centre of

curvature of a concave mirror and Fig. 68 shows the position and the character of the image of the object placed before a convex mirror.

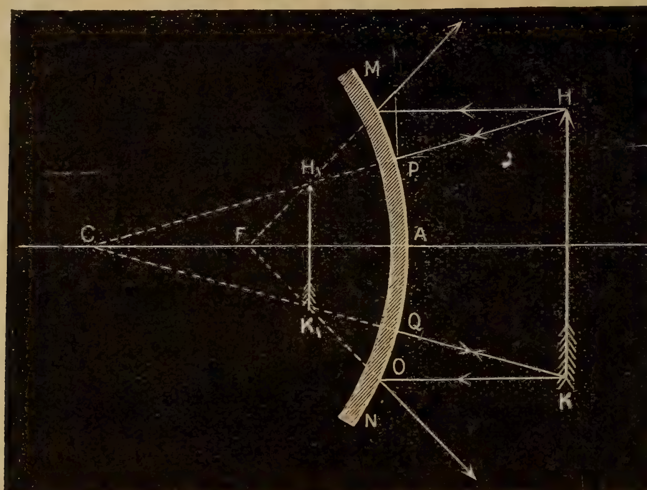


FIG. 68.

Make drawings showing the position and the character of the image of an object placed (1) between the centre of curvature and the principal focus, (2) between the principal focus and the mirror, (3) at the centre of curvature, (4) at the principal focus of a concave mirror.

16. Caustics—Spherical Aberration.

Experiment 3.

Take a strip of bright polished metal and bend it into semi-circular form. Stand it on a sheet of white paper and place a lighted candle in front of its concave surface as shown in Fig. 69. Make a sketch on the paper showing the way in which the light is focused.

Experiment 4.

Project the image of a lighted candle on a screen with a concave spherical mirror. Observe the brightness and the sharpness of the image. Now cover the outer edge of the

mirror with black paper, leaving only a small reflecting surface near its centre, and again project the image of the candle on the screen.

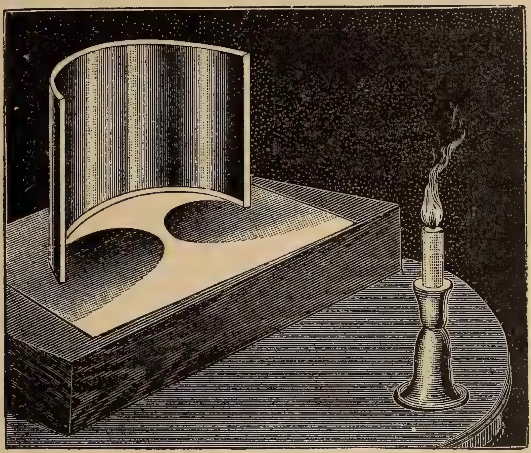


FIG. 69.

How does the image differ from the former one in (*a*) brightness, (*b*) sharpness of definition? How do you account for the difference?

The effects noted in the preceding experiments are due to the fact that all rays falling on the surface of a large concave spherical reflector do not after reflection cross the principal axis at the same point, rays incident near the margin of the mirror crossing nearer the mirror than those which are incident upon it nearer its centre. The

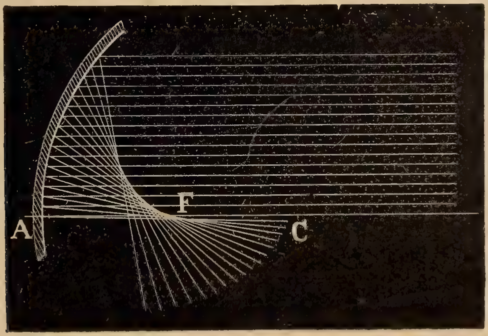


FIG. 70.

intersections of the reflected rays with one another form a curve known as the **caustic**. Fig. 70 shows the form

of caustic produced by rays parallel to the principal axis.

Allow sunlight to fall on the side of a basin nearly filled with milk, observe the caustic on the surface.

The non-coincidence of foci produced by rays reflected from different sections of the surface of a mirror cause an indistinctness in the images formed by it This is due to what is called the **spherical aberration** of the mirror. It is corrected by making the aperture of the mirror very small, not more than 10°, or by decreasing the curvature of the mirror from the centre outwards as is done in the parabolic reflectors in common use for head-lights, search-lights, etc.

QUESTIONS.

1. Determine by drawing accurately the paths of four rays, two proceeding from each end of an object 2 inches high, placed symmetrically on the axis of a concave mirror of 4 inches focal length at 6 inches from it, the height and the position of the image.

2. The radius of curvature of a concave spherical mirror is 20 cm. If the rays diverge from a point 60 cm. in front of the mirror, at what point will they focus?

3. A gas-flame is 36 inches from a concave reflector when its image is 50 inches from the reflector. Find the principal focal length and the radius of curvature of the mirror.

4. Find the principal focal length of a concave spherical mirror whose radius of curvature is 24 inches, and find the position of the images of points situated (*a*) 18 inches, (*b*) 36 inches, (*c*) 8 inches in front of the mirror.

5. If you look at yourself in a convex spherical mirror you see an upright image of yourself. Under what circumstances can you see an upright image of yourself in a concave spherical mirror?

Explain by means of a diagram the directions of the rays by which the images are seen.

6. Interpret the formula $\frac{1}{u} + \frac{1}{v} = \frac{2}{r}$ in the case of a virtual image.

7. Show by a geometrical construction that the size of the image formed by a spherical mirror is to the size of the object as the distance of the image from the mirror is to the distance of the object from the mirror.

CHAPTER IX.

REFRACTION OF LIGHT.

I.—Laws of Refraction.

1. Refraction.

Experiment 1.

Arrange apparatus as shown in Fig. 71. The front and ends of the rectangular tank are glass, and the remainder is made of metal. The sides are about 30 cm. square and 5 cm.

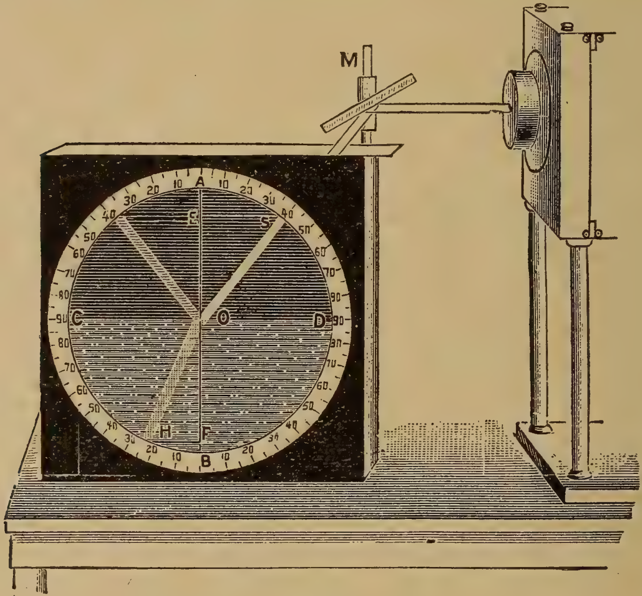


FIG. 71.

apart. The top is closed by a movable metal strip about 10 cm. longer and 4 cm. wider than the opening. A slit 3 cm. long and 1 millimetre wide is cut crosswise in this strip at a distance of about 10 cm. from the end. The whole tank, except the glass ends and a circle about 30 cm. in diameter

on the glass front, is painted inside and out a dead black. Horizontal and vertical diameters are drawn across the circular opening, and its margin is graduated in degrees, the extremities of the vertical diameter being marked zero.

The tank is filled with water to the horizontal diameter. A cap with a narrow horizontal slit is placed on the tube of the lantern or porte lumiere, and a thin beam of light is reflected by the mirror M, and made to pass through the slit in the movable top of the vessel and strike the water at O, the centre of the circle. The edge of the beam should be parallel with the front of the tank.

Observe the change in the direction of the beam at the point where it enters the water.

The change in direction which takes place in rays of light in passing obliquely from a medium of one density to a medium of a different density, for example, from the air to the water in the tank, **is called refraction.**

The **incident ray** is the direction, SO, which the light takes in the first medium; and the **refracted ray** the direction, OH, which it takes in the second medium.

The angle SOA, which the incident ray makes with a line, AB, drawn at right angles to the surface separating the two media is called the **angle of incidence**; and the angle HOB, which the refracted ray makes with this line is called the **angle of refraction.**

The ratio, $\frac{SE}{SO}$, of the perpendicular SE to radius SO is **the sine of the angle of incidence**; and the ratio, $\frac{HF}{HO}$, of the perpendicular HF to the radius HO **is the sine of the angle of refraction.**

2. Laws of Refraction—Experimental Verification.

Experiment 2.

Repeat Experiment 1 several times, changing each time the angle of incidence by adjusting the mirror and changing the position of the slit in the movable top of the vessel. For large angles this movable strip is placed along the glass end of the vessel.

1. Observe that when the edge of the incident beam is parallel with the glass face of the vessel, the refracted beam is also in the same plane.

2. Read on the graduated scale the measure of the angle of incidence and that of the angle of refraction each time the experiment is made; and measure in each case the length of the perpendiculars SE and HF, and calculate the value of the sine of the angle of incidence, and the sine of the angle of refraction. Tabulate your results as follows:—

No. of Experiment.	Angle of Incidence.	Sine of the Angle of Incidence.	Angle of Refraction.	Sine of the Angle of Refraction.	Ratio of the Sine of the Angle of Incidence to the Sine of the Angle of Refraction.
	In Degrees =	$\frac{SE}{SO}=$	In Degrees =	$\frac{HF}{HO}=$	$\frac{SE}{SO}\div\frac{HF}{HO}=\frac{SE}{HF}=$
1					
2					
3					
Etc.	Etc.	Etc.	Etc.	Etc.	Etc.

If the measurements are made with care, $\frac{SE}{HF}$, the ratio of the sine of the angle of incidence to the sine of the angle of refraction, will be found to be approximately constant for all angles of incidence. Carefully repeated experiments show that this law holds for other media.

Hence, from 1 and 2, we have the following laws:—

3. Laws of Refraction.

(1) **The incident ray and the refracted ray are in the same plane, which is perpendicular to the surface separating the two media.**

(2) **Whatever the obliquity of the incident ray, the ratio which the sine of the angle of incidence bears to the sine of the angle of refraction is constant for the same media, but varies with different media.**

4. Index of Refraction.

The ratio of the sine of the angle of incidence to the sine of the angle of refraction is called **the Index of Refraction.** It is generally denoted by the letter μ.

From air to water	- -	$\mu = 4/3$
" " " crown glass	- -	" $= 3/2$
" " " flint glass	-	" $= 8/5$
" " " carbon disulphide		" $= 5/3$
" " " diamond	- -	" $= 5/2$

5. Explanation of the Phenomena of Refraction.

The change of direction of a ray of light at the surface separating two media is a result of a change of velocity

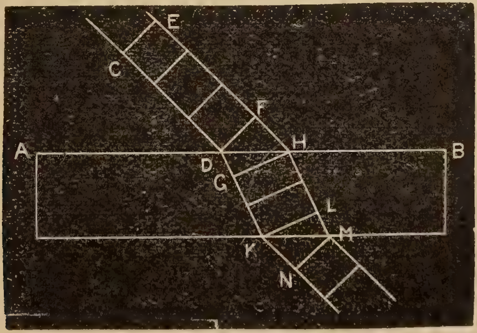


FIG. 72.

at this surface. A beam of light has a wave-front across it, that is, at right angles to the direction of its rays.

Now imagine a wave whose front is DF to be incident obliquely upon a refracting surface AB, the lower medium being the denser (Fig. 72). When the ray CD has reached the surface at D, the ray EF has reached the point F. The ray CD is travelling more slowly in the denser medium and, therefore, passing through a shorter distance DG, while the ray EF is still travelling more rapidly in the rarer medium and passing from F to H. Hence the direction of the wave-front is changed to the direction GH in the denser medium; and normals to this line, GK, or HL will represent the direction of the rays in this medium.

Again, in passing out of this medium to one of the same density as the first, the ray GK travels more rapidly in the rarer medium a greater distance from K to N, while the ray HL travels more slowly in the denser medium from L to M, and consequently the direction of the wave-front is again changed.

6. To Construct the Refracted Ray.

Let CD (Fig. 73) be the surface separating the two media, say air and water, and PO, a ray of light incident at O. It is required to draw the refracted ray. With O as a centre, and with radii in the ratio 4 : 3, describe two concentric circles. Through H, the point of intersection of PO and the circumference of the smaller circle, draw the line FK parallel to the normal AB. Join F and O, and produce FO to Q. Then OQ will be the refracted ray.

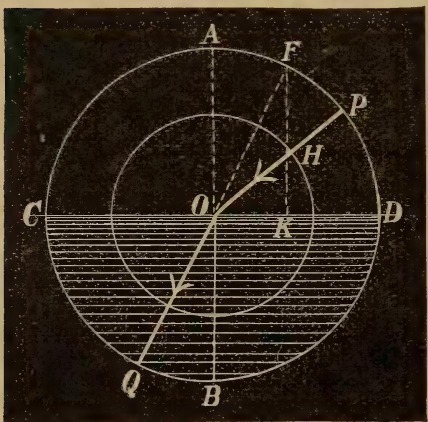


FIG. 73.

Since angle of incidence, AOP = OHK,
and angle of refraction, QOB = AOF = OFK,

$$\frac{\sin AOP}{\sin QOB} = \frac{\sin OHK}{\sin OFK} = \frac{\frac{OK}{OH}}{\frac{OK}{OF}} = \frac{OF}{OH} = \frac{4}{3}$$

QUESTIONS.

1. Trace a ray of light from :

(1) water into air,
(2) air into flint glass,
(3) crown glass into air,
(4) air into carbon disulphide,
(5) diamond into air,
(6) water into crown glass,
(7) crown glass into flint glass.

2. A wavy appearance is observed in the air over a hot iron. Explain the cause. Explain also the streaky appearance of water in which sugar is being dissolved.

3. If lines are drawn on paper, and a piece of plate glass placed over a portion of the lines, the lines appear broken off at the edge of the glass when viewed obliquely (Fig. 74). Explain the reason.

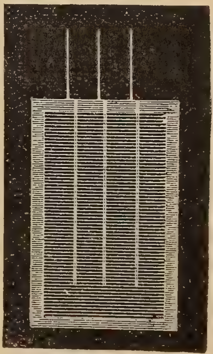


FIG. 74.

4. You look through a thick plate of glass at a vertical pole, the glass being held so that a part of the pole is seen directly and part through the glass. Describe and explain the change in the apparent position of the part of the pole which is seen through the glass, when the latter is turned about a vertical axis.

5. A thick glass plate is interposed obliquely between a lighted candle and the observer's eye. Will the apparent position of the candle be altered by the glass? Explain by means of a diagram.

6. A colourless solid is dropped into a colourless liquid, and the solid is invisible in the liquid. How are the refractive indices of the liquid and the solid related? Why?

II.—Total Reflection.

Experiment 1.

Arrange apparatus as shown in Fig. 75. The movable strip is placed against the end of the tank used in Experiment 1,

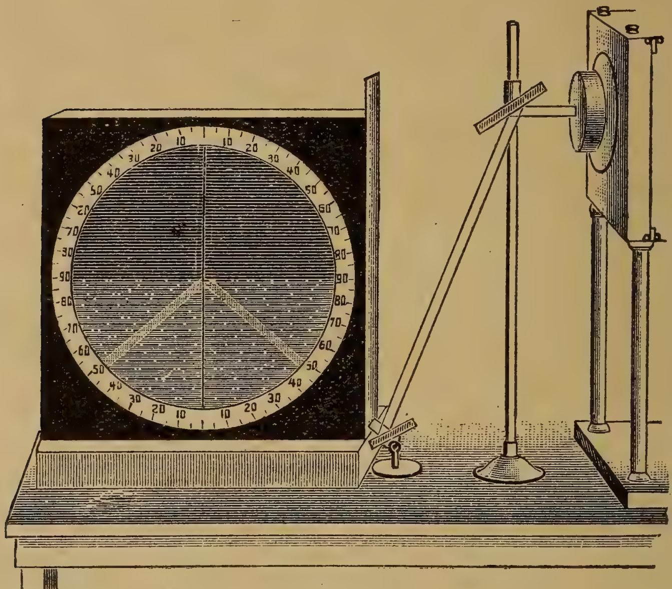


FIG. 75.

page 96. By means of two mirrors cause a thin beam of light to enter a slit placed at the **bottom** of the tank and to pass through the water to the centre of the circle.

1. What is the course of the light after it reaches the surface of the water?

2. What is the measure of the angle which the incident beam makes with the normal?

3. The light is refracted in passing from the denser to the rarer medium; which is the greater, the angle of incidence or the angle of refraction?

Make the angle between the incident beam and the normal greater by moving the slit upward and adjusting the mirrors.

Observe that the refracted beam approaches nearer and nearer the surface of the water, and finally passes out along the surface, and then into the water.

1. What angle does the incident beam make with the normal when this takes place?

When the angle of incidence is made greater than this angle, the light does not leave the water, but is reflected from its upper surface as from a mirror.

7. Explanation of Phenomena of Total Reflection.

To explain the phenomena, consider Fig. 76. Since the angle of incidence is greater than the angle of refraction when a ray passes from a rarer to a denser medium, the refracted ray OH will still make an angle HOB, which is less than a right angle, with the normal, and will then be within the denser medium when the angle of incidence is 90°, that is, when the incident ray just grazes the surface separating the two media. Now it is evident that if the process is reversed and the light is sent back from the denser to the rarer medium along the line HO, the refracted beam will just graze the surface separating the media, and that, if the angle of incidence is less than the angle HOB, it will pass up into the rarer medium according to the laws of refraction. If the angle of incidence POB becomes greater than HOB the incident ray on reaching the point O passes into the denser medium again, or is reflected in the direction OQ, from the surface separating the media.

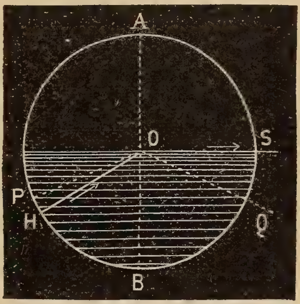


FIG. 76.

The limiting angle of incidence, HOB, which allows a ray travelling in a denser medium just to escape into a rarer one, is called the **critical angle.**

The reflection of light from the surface of separation of two media when the incident ray is in the denser medium and the angle of incidence is greater than the critical angle, is called **total reflection.**

From water to air the critical angle is 48° 35′.

8. To Construct the Critical Angle.

Let CD (Fig. 77) be the surface separating the media, say air and water. With O as a centre and with radii in the ratio 4:3 describe two concentric circles. The ray issuing from the water must be in OD. From S, the point of intersection of OD with the smaller circle, draw the line SE parallel with the normal AB. Join E and O and produce the line EO to H. Then HO will be the incident ray and the angle HOB will be the critical angle. (Art. 6, page 100).

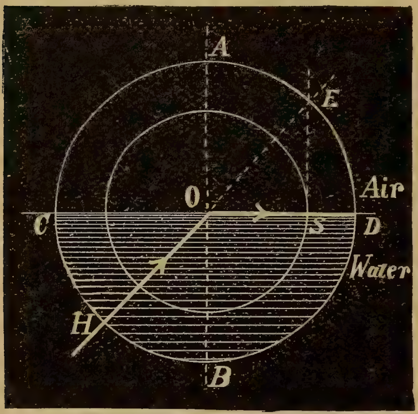


Fig. 77.

QUESTIONS.

1. Construct the critical angle for:
   (1) crown glass,
   (2) diamond,
   (3) carbon disulphide.

2. If a beam of light is passed into a right-angled glass prism, ABC (Fig. 78), in the direction OH, it passes out in the direction HI at right angles to OH, and the image of any luminous object placed at O appears at O_1. Explain. If you have a prism, place it in the path of a beam of light from a lantern and observe the change in the direction of the beam.

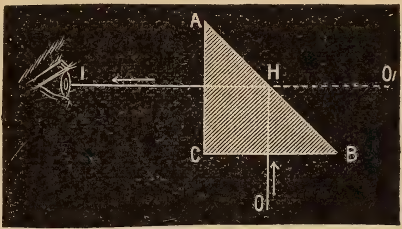


FIG. 78.

3. If a thick rectangular piece of glass (a paper weight answers well) is placed on a printed page, the print can be read when the eye is directly above it, but if the position of the eye is gradually changed, and the page is viewed more and more obliquely, a point is reached when the print suddenly becomes invisible. Explain.

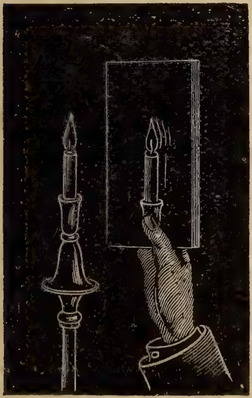


FIG. 79.

4. If an empty test-tube is thrust into water and placed in an inclined position, the immersed part appears, when viewed from above, as if filled with mercury. If the tube is now filled with water the brilliant reflection disappears. Explain the phenomena.

5. If you hold a glass of water with a spoon in it above the level of the eye and look upward at the under surface of the water, you are unable to see the part of the spoon above water, and the surface of the water appears burnished, like silver. Explain.

6. If a lighted candle is held obliquely before a piece of thick plate glass several images of the candle (Fig. 79) are

seen. Explain, by means of a diagram, how these images are formed.

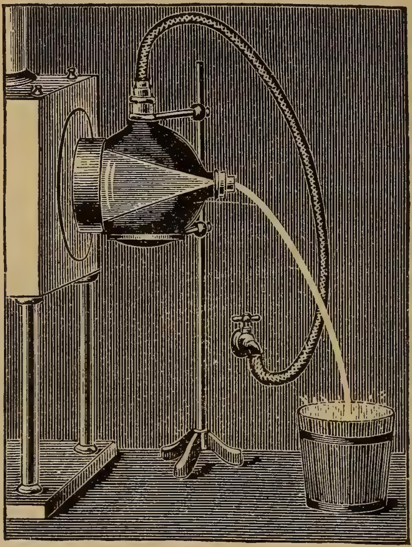


FIG. 80.

7. If a pencil of strong light is brought to a focus at the point where water is issuing in a thin stream from a vessel (Fig. 80), the light instead of escaping into the room remains within the stream and illuminates it intensely. Explain.

Try the experiment. The vessel is an ordinary receiver used with retorts. All its outer surface except the circle at which the

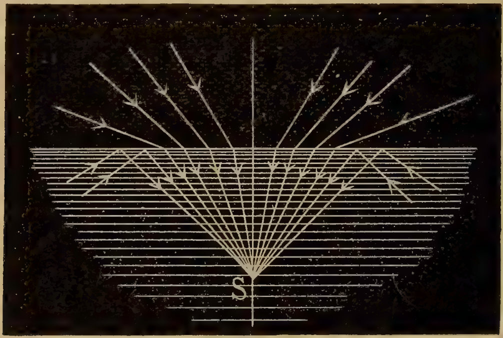


FIG. 81.

light enters is painted black. The water from any source of supply enters by the rubber tube, and passes out in a stream through a

glass tube inserted in a cork. The vessel is placed in such a position before the lantern or porte lumiere that the light is brought to a focus at the point where the water leaves the vessel.

8. Why does an observer at the bottom of a pond in looking upwards through the water see all objects outside as if they were crowded within a cone, while beyond this cone he sees by reflection objects lying on the bottom of the pond? (See Fig. 81).

III.—Refraction in Media Bounded by Plane Inclined Surfaces—Prisms.

Experiment 1.

Slide the condensers into the tube of the lantern or porte lumiere, and over the tube place a cap with a narrow vertical slit. By means of the lantern objective or a single lens, focus the slit on the screen.

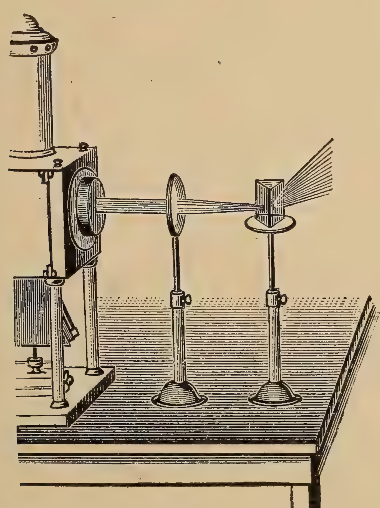


Fig. 82.

Now support a glass prism of 60° angle close to the objective lens, between it and the screen, and turn it around until the light is seen to pass through it (Fig. 82).

1. What change in direction in the light takes place in passing into and out of the prism?

2. Give a reason for this change in direction? To answer this question refer to Fig. 83, and read again Art. 5, page 99.

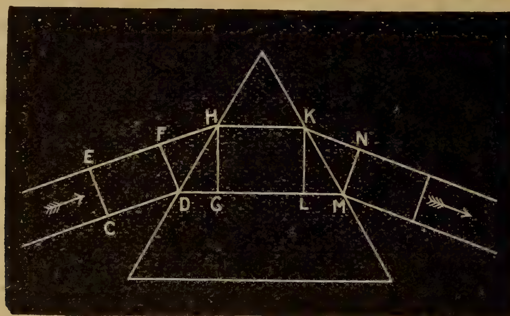


FIG. 83.

3. Why does the light emerge from this prism, while it is reflected from a side of a right-angled prism, as shown in Fig. 185?

Experiment 2.

Place a bright object opposite one face of the 60° prism and look at it through the prism.

How must the eye be placed to see the object? Why?

9. To find by a geometrical construction the path of a ray of light through a triangular glass prism.

Fig. 84 shows how the path of a ray of light DE may be traced through a prism by the method described in Art. 6, page 100.

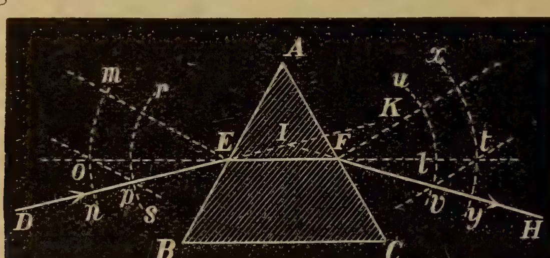


FIG. 84.

E m is the normal to the surface of the lens, and OP is drawn parallel to it from the point of intersection of the ray and the circumference of the smaller circle.

OE, therefore, represents the direction of the ray through the glass. Similarly FH is found to be the path of the ray on emerging from the glass.

1. Draw accurately the path of a ray of light, through a 45° prism of glass, whose index of refraction is 8/5, drawing the ray incident on one face in a direction perpendicular to the other face.

2. The angles of a glass prism are 90°, 70°, and 20°, and a ray of light enters the prism normally at the face bounded by the angles 90° and 70°. If the refractive index of the glass is 3/2, determine by a construction the path of the ray through the prism.

IV.—Refraction in Media Bounded by Curved Surfaces.—Lenses.

A lens is any portion of a transparent medium bounded by curved surfaces. There are two classes :—

1. **Converging lenses,** those thicker at the centre than at the edge. Fig. 85 shows the three forms of these.

FIG. 85.

All these lenses are usually called **convex.**

2. **Diverging lenses,** those thinner at the centre than at the edge. The three forms of these are shown in Fig. 86. The term **concave** is applied to all lenses of this class.

FIG. 86.

We have already observed in a number of experiments that lenses of the first class cause rays of light to become convergent. To understand the reason for this, imagine the section of the lens to be made up of a succession of prisms of gradually increasing angle placed with their bases inward (Fig. 87). The rays of light in passing through these prisms are bent towards their bases, the amount of deviation increasing with the angle of the prism. The rays, therefore, which pass through them are rendered more convergent.

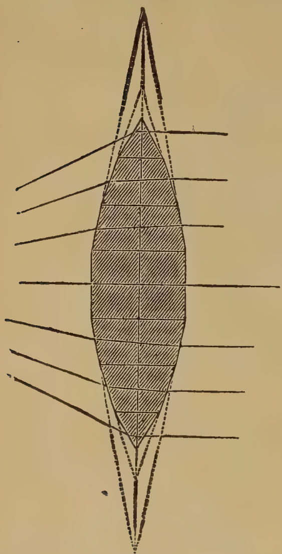


Fig. 87.

In the same way, lenses of the second class may be supposed to be made up of a succession of prisms with their apices inward; consequently their effect is to render the light which passes through them more divergent.

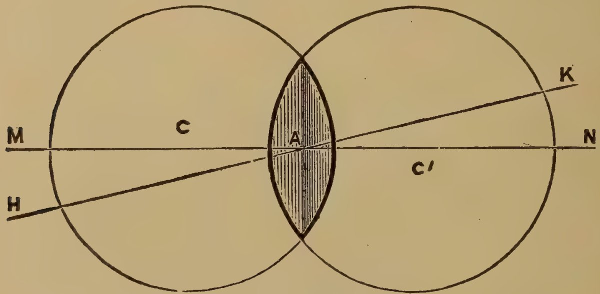


Fig. 88.

10. Axis, Optical Centre, and Focus of a Lens.

Fig. 88 shows how a double convex lens whose surfaces are spherical is formed.

The points C, C_1, are the **centres of curvature.**

The line MN through C and C_1 is the **principal axis.** The point A is the **optical centre.**

Any other line HK drawn through the optical centre is a **secondary axis.**

Construct figures to show how the other forms of lenses with spherical surfaces are formed.

The point on the principal axis of a convex lens to which rays parallel with the axis converge after passing through the lens, is called the **principal focus.** Since the rays actually converge and are brought to a focus, the focus is **real.**

With a concave lens the transmitted rays diverge and appear to come from a point in front of the lens, which is the principal focus for a lens of this class. Since these rays do not in reality come from this point, but are parallel before incidence, the focus is **virtual.**

When any ray of light passes through the optical centre of a lens, the incident ray is parallel with the emergent ray, as shown in Fig. 89. If the thickness of the glass is not great the lateral displacement may be neglected, and **any ray passing through the optical centre may be regarded as passing straight through the lens without refraction.**

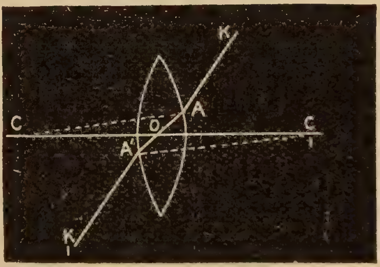


FIG. 89.

11. To Find by a Geometrical Construction the Path of a Ray of Light Through a Lens.

Fig. 90 shows how the path of a ray of light AB may be traced through a bi-convex lens whose index of

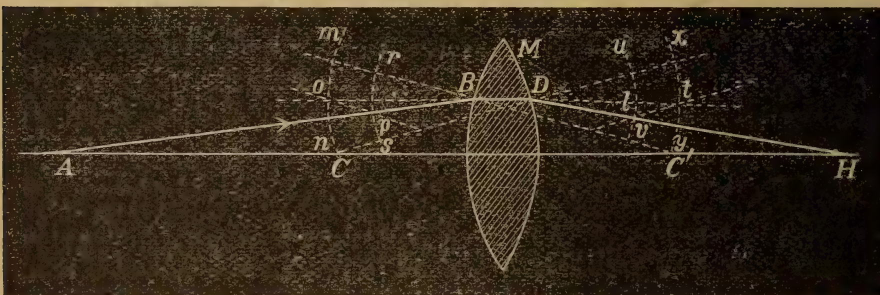


FIG. 90.

refraction is known by the method described in Art. 6, page 100. CB is the normal to the surface of the lens at the point of incidence, and *op* is drawn parallel to it from the point of intersection of the ray and the circumference of the smaller circle. oB, therefore, represents the direction of the ray through the glass. Similarly DH is found to be the path of the ray on emerging from the glass.

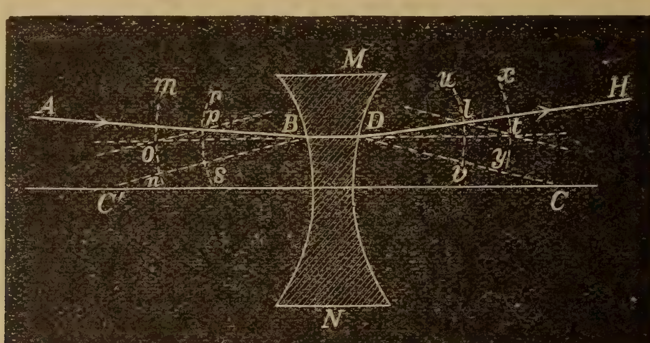


FIG. 91.

Fig. 91 shows a similar construction for the path of a ray through a concave lens.

12. To Find Experimentally the Principal Focus of a Converging Lens.

Experiment 1.

Mount the lens on a sliding piece of an optical bench and cause a small beam of light from a lantern or porte lumiere to be incident perpendicularly upon it (Fig. 92). Mount a

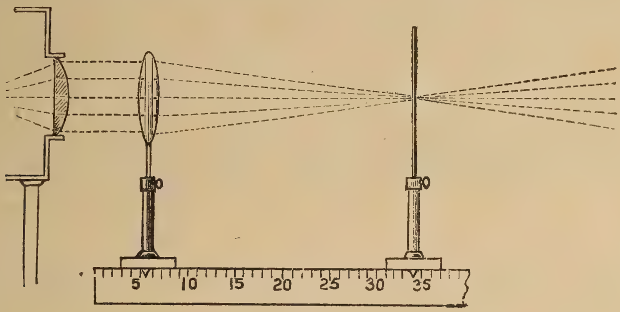


FIG. 92.

small screen on another sliding piece placed on the side of the lens opposite to the source of light. Move the screen up to the point where the spot of light falling on the screen is the smallest. Observe the distance on the scale between the screen and the centre of the lens.

What is the principal focal distance of the lens ?

13. To Find by a Geometrical Construction the Principal Focus of Converging Lens.

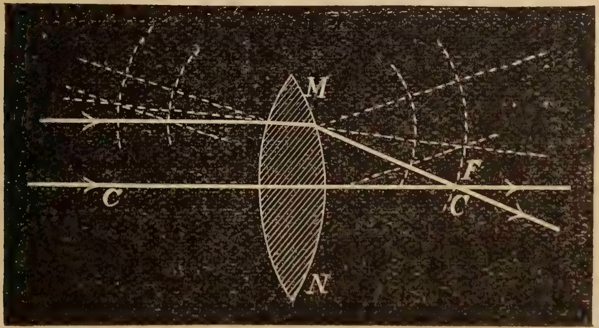


FIG. 93.

Fig. 93 shows how the principal focus of a lens may be determined by a geometrical construction when the

index of refraction of the material composing the lens is known. If the index of refraction is $\frac{3}{2}$, it will be found to be at the centre of curvature. Fig. 94 shows a

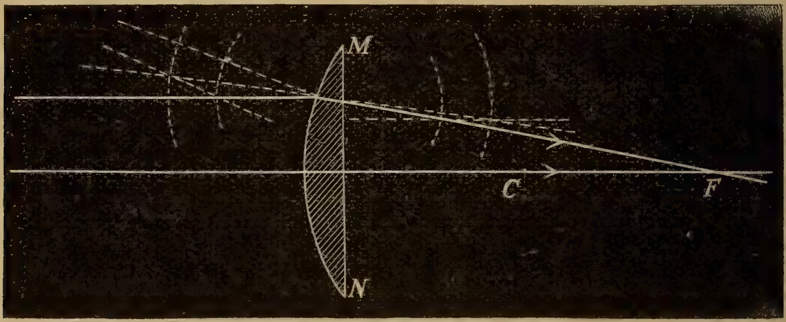


FIG. 94.

similar construction for a plano-convex lens. In this case if the index of refraction is $\frac{3}{2}$, the focal length will be twice the radius of curvature.

14. To Ascertain How a Convex Lens Disposes of a Pencil of Light.

Experiment 2.

Repeat Exp. 3, page 85, using a converging lens instead of a concave mirror.

1. Where do the rays focus when the light diverges (1) from a point beyond twice the focal distance, (2) at twice the focal distance, (3) at less than twice the focal distance, (4) at the focus, (5) from a point between the focus and the lens?

2. What is the course of the light when the lens is placed in the path of convergent light?

15. Conjugate Foci.

Can the point from which light diverges and the focus to which it is brought be interchanged? Try.

Two points so related that the light diverging from either is brought by a lens to a focus at the other, are called the conjugate foci of the lens.

If the position of one of the foci is known the position of the other can be determined by a geometrical construction as shown in Fig. 90, if the refractive index of the lens is known.

Fig. 95 shows that when the rays diverge from a point between the principal focus and the lens they are not brought to a focus on the opposite side of the lens, but are rendered less divergent, and leave the lens as if they diverged from a point farther from the lens than the point from which they really eminate. The focus is, therefore, virtual.

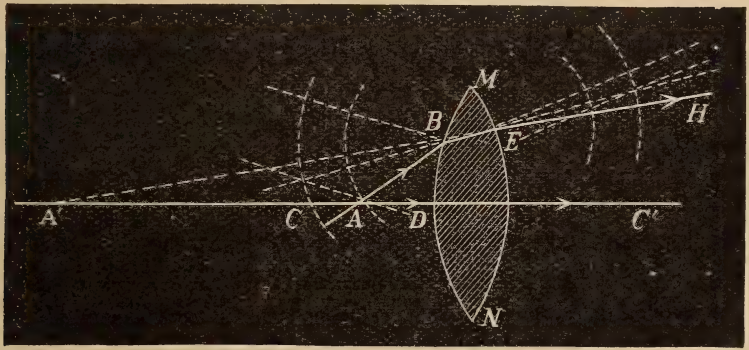


FIG. 95.

Repeat Experiment 2 to demonstrate that if u and v are the distances of the *conjugate foci from the optical centre of a lens, and f is the principal focal length of the lens, $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$ approximately.

16. To Find the Principal Focal Distance of a Concave Lens.

Experiment 3.

Cover one of the faces of the lens with paper in which is cut a smooth round hole 2 cm. in diameter exactly over the optical centre. Mount the lens on the sliding piece of an

optical bench, and cause a beam of light to be incident perpendicularly on the lens, the covered face of the lens being turned away from the light. Mount a cardboard screen on another sliding piece, placed on the side of the lens opposite to the source of light. Move the screen backward or forward until the disc of light on the screen is just 4 cm. in diameter. Observe the distance on the scale between the lens and the screen. This will be equal to the principal focal distance of the lens, as will be seen from the following considerations.

The rays which were parallel before reaching the lens diverge after passing through the circular opening BC (Fig. 96), and apparently come from a focus F in front of the lens. The focus is therefore virtual, and the principal focal length of the lens is AF; but when

$$B_1C_1 = 2\,BC$$

neglecting the thickness of the lens,

$$FD = 2\,FA$$

or $$FA = AD$$

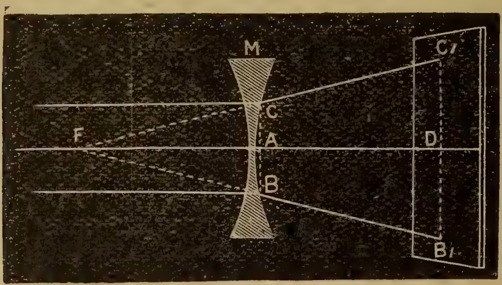


FIG. 96.

17. To Ascertain How a Concave Lens Disposes of Incident Light.

Experiment 4.

Repeat Experiment 2, page 114, using a concave lens instead of a convex one.

What change is produced in the direction of the rays when a concave lens is placed in the path of (1) a beam of light, (2) a divergent pencil, (3) a convergent pencil?

18. Summary.

The above experiments show that when rays from a luminous point on the principal axis of a lens fall upon it, the **transmitted rays** (1) **converge to another point on the principal axis,** or (2) **are rendered parallel with the principal axis,** or (3) **appear to diverge from a point on it.** When the rays transmitted actually pass through a point the focus is **real**; when they only appear to diverge from a point the focus is **virtual.**

With the convex lens the focus is real when the source of light is beyond the principal focus, and virtual when it is between the principal focus and the lens.

Show how you would find by a geometrical construction the principal focus of a concave lens whose index of refraction is known.

V.—Images formed by Convex and Concave Lenses.

19. To Determine Experimentally the Character of Images formed by Convex Lenses.

Experiment 1.

Support on a sliding piece of an optical bench a candle, a

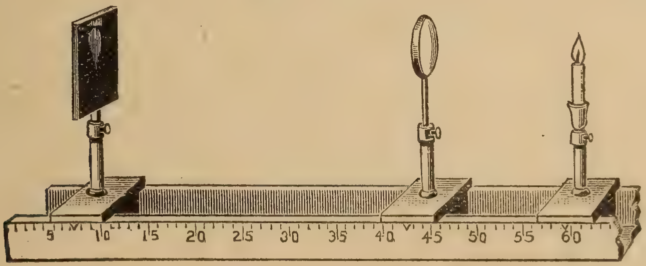


Fig. 97.

convex lens, and a cardboard screen in the order shown in Fig. 97, their centres being in the same horizontal line.

Place the candle at more than twice the focal distance from the lens. Move the screen backward, or forward, until a sharply defined image of the candle is formed on it.

1. Is the image real or virtual?

2. Is it larger or smaller than the candle? Is there any relation between the relative sizes of the candle and the image and the relative distances from the lens?

3. Is the image erect or inverted?

Move the candle gradually toward the lens, adjusting the screen as before.

1. What changes take place in the position and the size of the image?

2. Where is the image when the candle is at twice the principal focal distance? Where, when it is at the focus of the lens?

3. Where is the image when the candle is between the principal focus and the lens? To answer this question, place the eye on the side of the lens opposite to the candle, and look through the lens at the candle.

The above experiments show that with convex lenses:

1. **The image of an object placed more than twice the principal focal distance from the lens is real, inverted, and smaller than the object.**

2. **When the object is moved up toward the lens the image becomes larger, being equal in size to the object when it is at twice the focal distance, but remains real and inverted until the object reaches the focus, when the rays are rendered parallel and the image is at an infinite distance.**

3. **When the object is between the focus and the lens, the image is virtual, erect, and enlarged.**

Does the formula[1] $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$ hold approximately, when u and v are respectively the distances of the candle and its image from a convex lens whose principal focal length is f?

To answer this question repeat Experiment 1, page 117, taking careful measurements, and tabulating the results, as in Art. 13, page 90.

How may the formula $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$ be made use of to determine experimentally the focal length of a convex lens?

---

[1] This proposition may be demonstrated geometrically as follows:—

The parallel rays BD and CE may be regarded as being approximately refracted as shown in Fig. 98, where BC = DE.

Since the triangles B′A′C′ and BAC are similar

$$\frac{B'C'}{BC} = \frac{HA}{GA} = \frac{v}{u}$$

Again, since the triangles B′FC′ and DFE are similar

$$\frac{B'C'}{DE} = \frac{HF}{AF}$$

But DE = BC

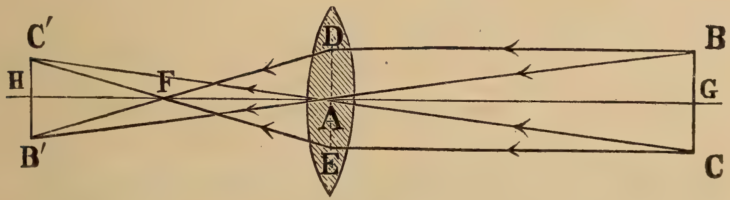


FIG. 98.

Therefore

$$\frac{B'C'}{BC} = \frac{HF}{AF} = \frac{v-f}{f}$$

Hence, equating the two values of $\frac{B'C'}{BC}$,

we have

$$\frac{v}{u} = \frac{v-f}{f}$$

or

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

20. To Determine Experimentally the Character of the Image Formed by a Concave Lens.

Experiment 2.

Look at a candle through a concave lens.

It will be found that the **image is always virtual, erect and smaller than the object.**

21. Drawing Images Formed by a Lens.

The images formed by lenses are located in a geometrical construction in the same way as the images formed by mirrors, by locating the images of certain points which determine the form and the position of the image. The image of a point is located by finding the point of intersection after refraction of two rays proceeding from the point. The rays of which the direction after refraction are usually most easily determined are (*a*) a ray parallel with the principal axis, which after refraction passes through the principal focus; and (*b*) a ray through the optical centre, which passes on through the lens without change in direction. (Art. 9, page 111.)

Fig. 99 shows the image formed by a convex lens

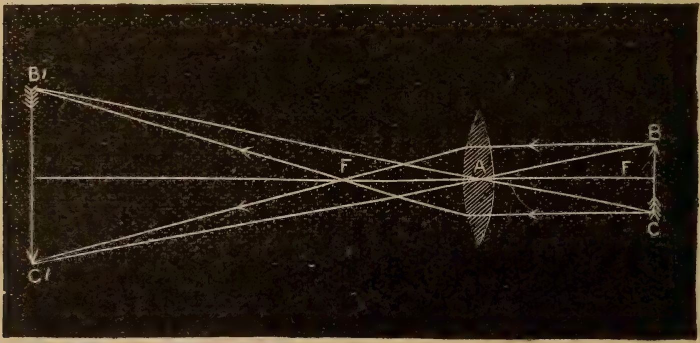


FIG. 99.

when the object is beyond the focus; and Fig. 100 shows the image formed by a concave lens.

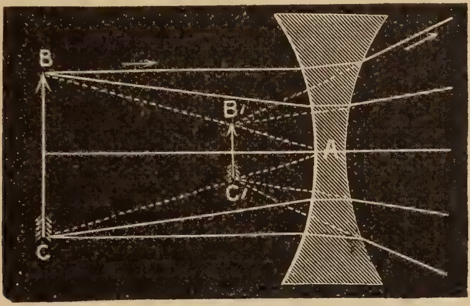


FIG. 100.

Make a similar drawing to show the image formed by a convex lens when the object is placed between the principal focus and the lens.

22. Spherical Aberration by Refraction.

It can be seen by a geometrical construction that the rays from a luminous point incident on the margin of a convex lens cross after refraction the principal axis nearer the lens than those incident upon it nearer its centre. This non-coincidence of foci causes, as in the case of the spherical mirror, a blurring of the image. It is corrected by the use of an annular stop or diaphragm to reduce the aperture of the lens, and in large lenses by using parabolic instead of spherical surfaces.

QUESTIONS.

1. An arrow five inches long is placed eight inches in front of a convex lens whose focal length is three inches. Find by a geometrical construction the length and position of the image.

2. Compare by an accurate construction the focal length of a lens of crown glass with that of a lens of flint glass, the lenses having the same shape and size.

3. The image of a distant bright point situated vertically over a vessel of water is formed on the bottom of the vessel by a convex lens immersed in the water. Would the distance of the lens from the bottom be the same if the vessel were filled with air? If not, explain with diagrams the cause of the difference.

4. If the image of an object 120 cm. distant from a convex lens is 10 cm. from the lens, what is its focal length?

5. Where must a screen be placed to receive the image of an object placed 24 cm. in front of a convex lens whose focal length is 20 cm.?

6. It is found when the image formed by a convex lens and the object are the same size they are 30 inches apart. What is the focal length of the lens?

7. The middle of a candle flame is placed in the axis of a convex lens, and at a greater distance from the lens but on the same side of it a plane mirror is arranged perpendicular to the axis. When a sheet of white paper is gradually brought near to the lens on the side remote from the flame and the mirror, images of the flame are seen in two positions. Explain this, and illustrate your explanation by a diagram.

8. Interpret the formula $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$ when the image of the object is virtual.

9. A convex lens of $4\frac{1}{2}$ inches focal length is held at a distance of 3 inches from a disc half an inch in diameter; find the position of the image of the disc.

10. A convex lens is focused on a mark on a sheet of paper; a thick plate glass is inserted between the paper and the lens, and it is found that the mark no longer can be distinctly seen. Explain this, and illustrate by a diagram the path of the rays in the two cases.

11. Prove by a geometrical construction that in both convex and concave lenses the size of the object is to the size of the image as

the distance of the object from the centre of the lens is to the distance of the image from the centre of the lens.

12. If the disc, question 9, is $\frac{1}{2}$ inch in diameter, what is the diameter of the image?

13. A concave lens of 6 inches focal length is employed to read the graduations of a scale and is held so as to magnify them three times. Find how far it is held from the scale.

CHAPTER X.

DISPERSION OF LIGHT—COLOUR.

I.—Dispersion.

1. Decomposition of White Light—Dispersion by a Prism-Spectrum.

Experiment 1.

Repeat Experiment 1, page 107, using a carbon disulphide bottle prism, if one is available, and placing a screen so that the rays transmitted by the prism will fall perpendicularly upon it (Fig. 101).

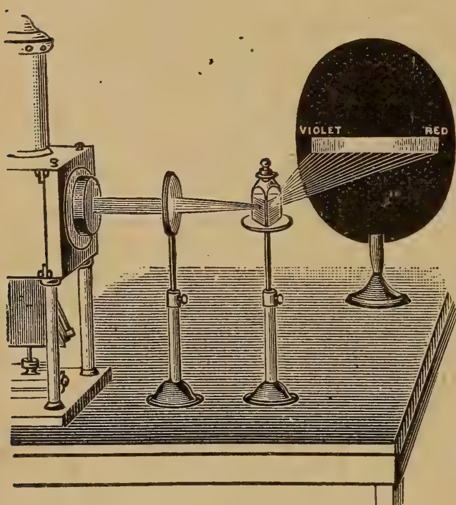


FIG. 101.

Observe the continuous band of colours on the screen. This is called **a spectrum**. Observe how one colour shades off into the next, passing from red at one end to violet at the other, through all the gradations of orange, yellow, green and blue.

The effect observed is due, as we have seen (Art. 6, page 272, Part I.), to the fact that the rays which give rise to the different colour sensations differ in refrangibility, and consequently are separated by being transmitted through the prism.

Experiment 2.

Look at objects through a glass prism.

Account for the fringes of colour which appear to surround them.

2. Recomposition of White Light.

Experiment 3.

Project, as in the last experiment, a spectrum on the screen, and place a second prism similar to the first with its apex turned in the direction of the base of the first, as shown in Fig. 102.

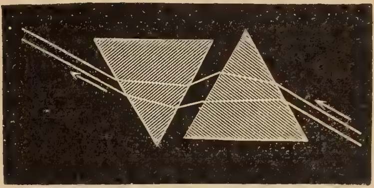


FIG. 102

1. Explain why there is now projected on the screen a white image of the slit instead of the spectrum.

2. Slide a piece of cardboard along gradually between the prisms, and account for the changes in the image.

Experiment 4.

Project a spectrum on the screen, and between the prism and the screen hold a large convex lens to receive the spectrum. Move it backward and forward along the line of light.

1. Is it possible to find a position of the lens where a white image of the slit is projected on the screen?

2. What does this experiment prove the coloured image to be?

3. Dispersion of Light by a Lens—Chromatic Aberration.

Experiment 5.

Place in the slide-holder of a lantern or porte lumiere a diaphragm with a small round hole. Project an image of the hole on a screen, using an ordinary bi-convex lens. Note the fringe of colour surrounding the image. The effect is due to the fact that different classes

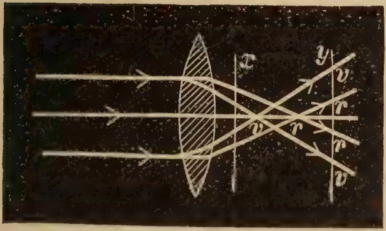


FIG. 103.

of rays are differently refracted by the lens, the violet coming to a focus nearest the lens, and the red at the greatest distance from it, as shown in Fig. 103, while between these lie the foci

of all intermediate colours. If a screen is placed at or near x, it will be bordered with red; if at y, with violet.

Lenses are made **achromatic** by combining in one two lenses differing widely in dispersive power in such a way that the dispersion by the one is neutralized by the other. Fig. 104 shows the ordinary form of combination of crown and flint-glass lenses for this purpose.

FIG. 104.

4. Modes of Producing Colour.

The physical characteristics of light which determine differences in colour sensations are differences in the wave-lengths of the ether waves falling upon the eye. For example, red is due to the longest waves, which have the power of exciting vision, and violet to the shortest, while the other colours are caused by waves whose wave-lengths are intermediate between these. Colour, therefore, is produced from white light by isolating waves of certain definite lengths. The common processes of separating the waves are

(1) Refraction.
(2) Absorption.
(3) Interference.

The experiments in the analysis of white light by dispersion described above illustrate the method of producing colour by refraction.

5. Colours by Absorption—Colours of Transparent and Opaque Bodies.

Experiment 6.

Project a spectrum on the screen. Hold over the slit in succession pieces of glass of different colours, red, green, blue, etc.

Do the glasses give colour to the light, or do they quench some of the colours existing in the light? How do you know?

The experiment shows that bodies have the power of exercising what is termed **selective absorption,** that is, they have the power of absorbing or quenching a part of the light-waves falling upon them, while they transmit the remainder. If a transparent body absorbs all components of white light in equal proportions, it is colourless; but if it is more transparent to certain classes of waves than to others, the character of the unabsorbed transmitted rays determines the colour which it is said to possess.

Experiment 7.

Again project a spectrum on a screen.

Pass a red ribbon through the spectrum near the prism.

What colour is it in the red, in the green, and in the blue parts of the spectrum respectively?

Repeat the experiment, using (1) a white ribbon, (2) a green one, and (3) a black one.

Experiment 8.

Procure strips of white, red, green, and blue paper, each of which should be about 3 cm. long and 2 mm. wide, and paste them apart on a sheet of black cardboard several times larger than the strips. Place the cardboard in a strong light and view each strip in order, beginning with the white one, through a glass prism, holding its edges parallel to the length of the strip.

Describe the appearance of each strip as seen through the prism.

These experiments show that the **colour of an opaque body** depends both upon the nature of the light falling

upon it and the unabsorbed light reflected by it. All bodies, except those with highly polished surfaces, reflect light in an irregular way from their internal surfaces. If white light falls upon a body, and if all the constituents of it are reflected in equal proportions, the body appears white or gray; but if the body exhibits any inequalities in its relative absorbing and reflecting power for light of different wave-lengths, the character of the unabsorbed and reflected rays determines its colour.

6. Colour by Interference.

Experiment 9.

Blow a soap-bubble and hold it in the sunlight. Note the rainbow-like bands of colour on its surface. The colours are produced by the waves reflected from the one surface of the film meeting and interfering with those reflected from the other. Where the waves meet in like phase, the colours of which they are the condition are strengthened; but where they meet in opposite phase, interference takes place, and the colours disappear. It is evident, therefore, that the colours which appear upon the film will depend upon the thickness of the film, a soap-bubble giving a red colour being thicker than one which gives a blue.

The colours observed when two pieces of plate glass are pressed together, or when a thin layer of oil spreads out over water are also due to interference.

7. Mixing of Colours.

Experiment 10.

Cut out of heavy paper several circular discs of different colours about 15 cm. in diameter. They should have a small hole at the centre, and be slit radially as shown in

Fig. 105, so that they can be slipped together, and mounted centrally on the axle of an electric motor or whirling machine, exposing any proportional parts of each (Fig. 106).

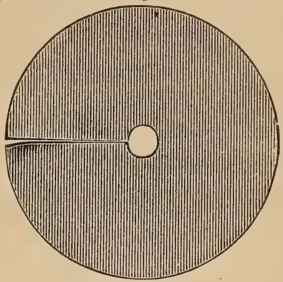


FIG. 105.

Select seven discs representing as nearly as possible the seven prismatic colours, and mount them on the spindle of the whirling machine or motor, exposing equal portions of the colours.

What is the colour of the disc when it is rotated rapidly in a strong light?

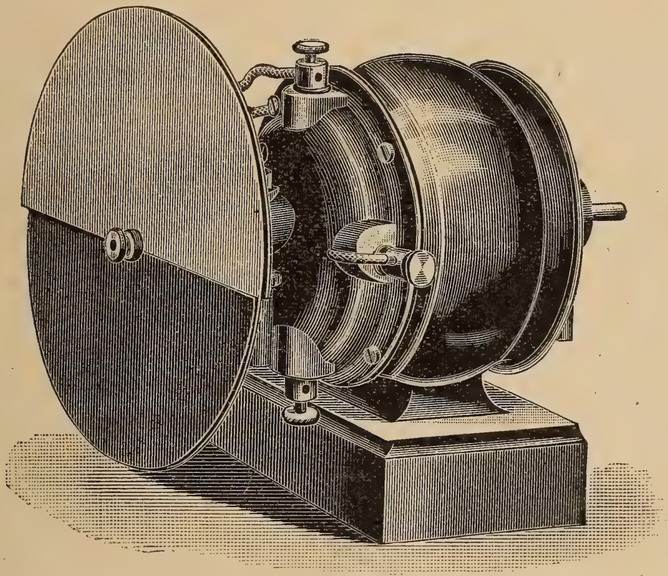


FIG. 106.

Repeat the experiment, using in succession discs of the following colours, exposing equal portions:—

(1) Red, green and blue.

(2) Orange and light blue.

(3) Green and purple.

(4) Yellow and indigo.

The method of mixing colours illustrated in the above experiment depends on the fact that when the colour disc is rotated rapidly, the sensations of colour experienced by the observer persist after the impressions which were their occasion have ceased, and while new impressions are falling upon the retina. This lagging of the colour sensations behind their stimuli produces an effect equivalent to the superposing of colours upon one another, as in the re-composition of white light (Experiments 3 and 4, page 125).

The experiments show that white light not only results from a combination of the prismatic colours, but that it is produced by a combination of certain colours selected from them.

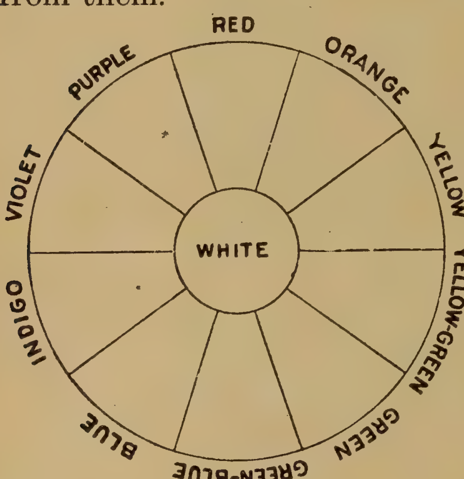


Fig. 107.

For example, it will be found that any two colours opposite each other in the colour circle (Fig. 107) gives, when mixed, gray, that is, white of low luminosity. Two colours whose mixture results in gray are said to be **complementary.** Every colour has some complementary in the spectral series, except green, whose complementary is purple, a mixture of red and blue.

8. Mixing of Pigments.

Experiment 11.

Mix chrome yellow and ultramarine blue pigments. What is the colour of the mixture? The experiment evidently

indicates that a mixture of pigments and a mixture of spectral colours may produce different results.

Experiment 12.

To discover the cause of the effect produced by the mixing of the pigments, project a spectrum on the screen as in Experiment 1, page 124, and place in the path of the light between the slit and the prism, first, a flat glass flask or cell containing a solution of copper sulphate, and then a similar cell containing a solution of bichromate of potash.

What parts of the spectrum are absorbed by each solution? What part remains unabsorbed by either?

It is evident from the experiments that green is a constituent of both the yellow and blue pigments which survives the absorption of the other elements and gives colour to the mixture.

Experiment 13.

If two projection lanterns are available (the combination used for producing dissolving-view effects is convenient), project two partially over-lapping circles of white light on the screen, and in front of the condenser of one lantern in the path of the light place one of the cells used in Experiment 12 above, and in front of the other condenser the second cell.

Account for the colour effects observed on the screen.

9. Undulatory Theory of Light.

We are now in a position to give a more extended statement of the undulatory theory of light than that given in Chapter XXIII, Part I.

1. *Light is radiant energy, or the energy of ether vibration, which can affect the eye and produce vision.*

2. *Difference in colour sensation is the result of difference in the vibration-frequencies, or the corresponding wave-lengths, of the ether-waves which fall upon the retina of the eye. Ether-waves of a certain wave-length give rise to one colour, those of another length to another colour, and so on.*

3. *The vibration-frequencies of the waves which form the red end of the spectrum are less, and their corresponding wave-lengths greater than those which form the violet end, the other colours being caused by waves whose wave-lengths are intermediate between these. The intermingling of waves of all these different lengths produces the sensation of white light.*

4. *In a dense medium, the short waves are more retarded than the long ones, and consequently are more refracted. Hence the dispersion of light by a prism.*

5. *Ether waves are absorbed, that is, the energy of ether vibration is changed into the energy of molecular vibration, or heat, when the molecular vibrations of a body are of such a character as to give rise to ether-waves of the same periods as those falling upon it. Hence the same body may transmit one class of waves and quench another.*

6. *While only those waves, whose vibration-frequencies lie between the limits of the extreme red and the extreme violet, have the power of exciting the optic nerves, and producing the sensation of colour, ether-waves, whose vibration-frequencies are either greater or less than these, may produce other effects. They may when falling on matter produce molecular vibrations, or heat. Certain classes of them also are instrumental in bringing about chemical changes.*

The "electric waves" by which wireless telegraphy messages are transmitted are probably ether waves similar in character to light but of very much lower vibration-frequency; while the "X-rays" are possibly irregular pulsations through ether, having a relation to light somewhat analogous to the relation of a noise to a musical note in sound.

Experiment 14.

Project a spectrum, and place in the path of the transmitted rays near the prism the face of a thermopile. Move it backward and forward across the path of the rays.

1. Does the needle of the galvanometer connected with the thermopile indicate the presence of heat on either side of the colour rays?

2. In what part of the spectrum does the thermopile indicate that the greatest quantity of radiant energy is being transformed into heat?

Experiment 15.

Tack on a board a piece of sensitized paper, which may be obtained from any dealer in photographers' supplies. Project a spectrum, and hold the board a short distance from the prism in such a position that the colours will be received on the sensitized paper. Keep it in the one position until the part of the paper on which the transmitted rays fall becomes decolorized by the chemical changes resulting from the action of the radiant energy.

1. Is there any decolorization at either end beyond the band of colours?

2. Where is the change in colour the greatest?

3. What classes of rays, therefore, are the most effective in bringing about chemical changes?

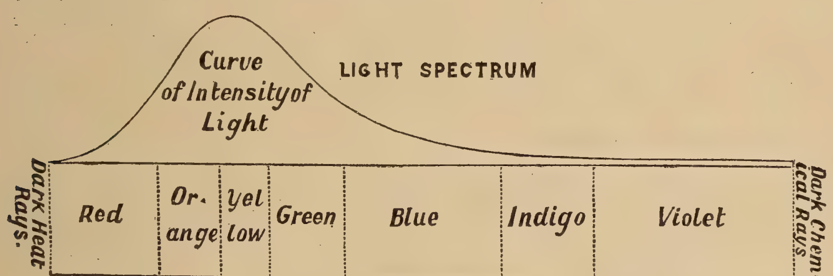


FIG. 108.

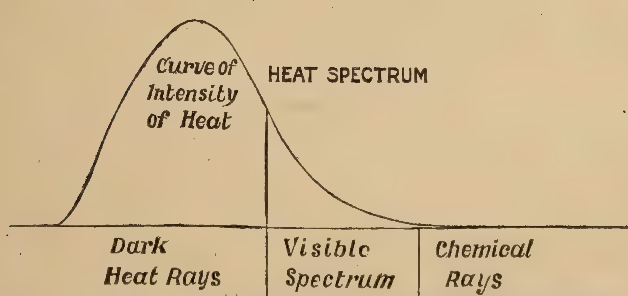


FIG. 109.

Figs. 108 and 109 show graphically the relative lighting and heating effects of the different parts of the spectrum.

CHAPTER XI.

MAGNETISM.

I.—Polarity.

1. Laws of Magnetic Attraction and Repulsion.

Repeat the experiments in verification of the laws of magnetic attraction and repulsion. (See Part I., pages 276–282.)

2. Theories of Magnetism.

We have shown (Art. 7, page 281, Part I.) that the two poles of a magnet are inseparable.

The co-existence of two poles in even the smallest part of a magnet is usually explained on the *theory that the molecules of a magnetic body possess polarity.*

When the body as a whole apparently possesses no magnetic properties, the opposite poles of adjacent molecules neutralize one another (Fig. 110*a*)*; but when it is magnetized, the greater number of the molecules are turned into lines, with their N-seeking poles turned in one direction and their S-seeking poles in the opposite direction.*

FIG. 110*a*.

FIG. 110*b*.

When, therefore, the magnet is broken at any point, one face of the fracture is a N-seeking and the other a S-seeking pole.

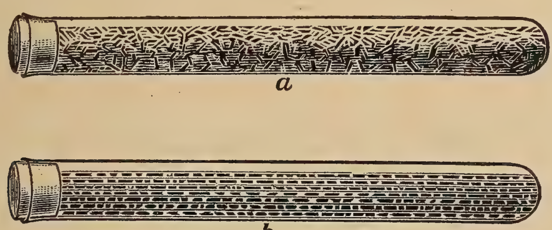
If the magnetization were equal at all points of the magnet, and the molecules were all arranged in line with their magnetic axes parallel to the axis of the magnet, with like poles all pointing in one direction (Fig. 110*b*),

free poles would be found only at the end surfaces; but this is not the case, because we have found that complete neutralization takes place only near the centre of the magnet. The intensity of magnetization must, consequently, be greatest at the middle of a bar of steel, and less toward its ends.

The theory of molecular polarity may be illustrated by the following experiment:—

Experiment 1.

Fill a test-tube nearly full with steel filings (Fig. 111*a*); magnetise it by drawing one pole of a strong magnet over the tube repeatedly in the same direction. Observe that the filings set themselves end-ways (Fig. 111*b*).



a

b

Fig. 111.

Without disturbing the arrangement, bring one end of the tube near (1) the N-seeking pole, (2) the S-seeking pole of a suspended magnetic needle.

What evidence have you that the tube filled with steel filings acts as a bar magnet?

Disturb the arrangement of the filings by shaking the tube, and again present one end of the tube to each pole of a magnetic needle.

1. Does the tube now act as a bar magnet? How do you know?

The tube filled with steel filings is shown to be a magnet when the magnetic axes of the individual pieces

of steel making up the filings are parallel with the length of the tube, similar poles being turned in the same direction; but when this arrangement is disturbed, and these individual pieces of steel turn in various directions, their poles neutralize one another, and the tube as a whole no longer acts as a magnet.

In a similar manner, the magnetic action of steel is believed to depend on the arrangement of the molecular magnets of which it is built up.

3. Consequent Poles.

All magnets must have, as we have learned, at least two poles; but, on account of irregular or imperfect magnetization, a piece of steel may be made to have one or more poles between those at the ends. These are called **consequent** poles. The magnet in this case may be regarded as consisting of two or more magnets placed end to end with similar poles together.

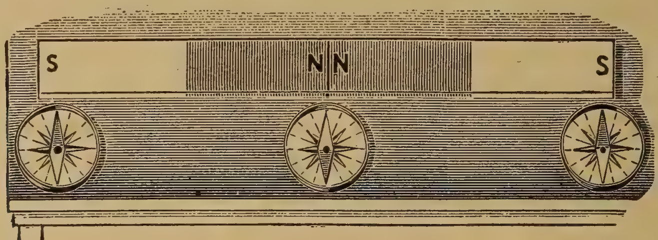


Fig. 112.

Experiment 2.

Take two similar magnets of equal strengths, and place them end to end with similar poles together, say two N-seeking poles together (Fig. 112). Determine the position of the poles by bringing a suspended magnetic needle in different positions (1) near each end, (2) near the point of junction.

1. What pole is found to be at each end of the joined magnets? What pole at the middle, or point of junction?

2. If two S-seeking poles were placed together, what would be your answers to the last question?

3. If three magnets were placed as shown in Fig. 113, what would be the distribution of the poles?

FIG. 113.

Experiment 3.

Place like poles of two bar magnets at the middle of a piece of watch spring and draw them simultaneously to the ends. Now lift them up, place them at the centre, and draw them to the ends. Repeat the operation several times. Remove the magnets, and determine the distribution of the poles in the watch spring by passing a suspended magnetic needle around the spring, and noting the direction in which the poles of the needle point in its various positions.

What pole is in the middle of the spring? What at each end?

QUESTIONS.

1. A bar magnet, freely suspended horizontally, sets itself north and south. If a second bar magnet is suspended by the side of the first, how will they act upon each other? Make your answer clear by a diagram.

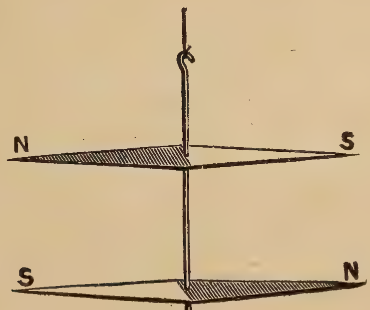


FIG. 114.

2. Two magnetic needles connected rigidly by a wire, as shown in Fig. 114, are called an **astatic pair**. In what direction will they set themselves when suspended by a fibre?

3. You are doubtful whether a steel rod is neutral, or is slightly magnetized; how could you determine its magnetic condition by trying its action upon a compass-needle?

4. A bar magnet is placed anywhere on the table in the neighbourhood of a compass needle, and is slowly rotated round a vertical axis through its middle point. Describe the behaviour of the needle (1) when the magnet is very close, (2) when it is a few feet distant.

5. Six magnetized sewing-needles are thrust through six pieces of cork, and are then made to float near together on water with their N-seeking poles upward. What will be the effect of holding (1) the S-seeking pole, (2) the N-seeking pole, of a magnet above them? Try the experiment.

6. A bar magnet is placed anywhere on the table in the neighbourhood of a magnetic needle, and is slowly rotated round a vertical axis through its middle point. There are two positions of the magnet for which the needle points along the line of its undisturbed position. Explain this.

7. Two bar magnets of equal length are set on end a few inches apart. A small magnetic needle is carried round the upper poles in a figure-of-eight course. How will it point in the various positions occupied, (1) when the upper poles are *like* poles; (2) when they are *unlike* poles?

8. A strong bar magnet is placed on a table with its north pole pointing toward the north. State in what direction a compass needle points (1) when placed immediately over the centre of the bar magnet, (2) when gradually raised vertically upwards.

9. A compass-needle is suspended at the centre of a circle drawn on a horizontal table. A magnet is moved round the compass so that its centre always lies in the circumference of the circle and its length always points east and west. How and why will the position of the compass-needle change as the magnet is carried round it?

10. A piece of steel wire, bent so as to form two sides of a square, is magnetized in such a way that each of its free ends is a north pole, and the bend a south pole. When placed upon a cork floating in water, how will it set itself?

II.—Magnetic Induction.

4. Phenomena of Induction.

Repeat the experiments illustrative of the phenomena of induction. (See Part I., pages 282, 283.)

Experiment 1

Place a strong magnet on a table, and suspend by means of a wire stirrup and fibre a bar of soft iron over it (Fig. 115).

1. What position does it take? Why?

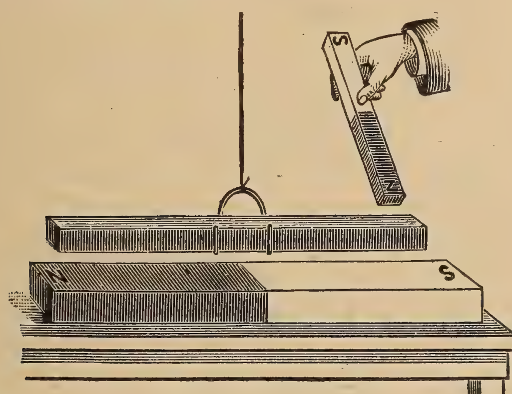


FIG. 115.

2. What happens when (1) the N-seeking pole, (2) the S-seeking pole of another magnet is placed, as shown in the figure, near the end of the soft iron over the S-seeking pole of the first magnet? Explain.

5. Explanation of Induction.

The phenomena of induction can be explained on the theory of the polarity of the molecules. *When one of the poles, say the N-seeking pole, of a magnet is brought near the end of the rod of soft iron, the attractions and repulsions between it and the magnetic molecules of the soft iron cause these molecules to turn around and arrange themselves with their S-seeking poles turned toward the N-seeking pole of the magnet. The bar, like the tube containing the steel filings (Fig. 111), then shows polarity, its S-seeking pole being at the end of the rod nearest the N-seeking pole of the magnet.*

When the magnet is removed, the mutual attractions and repulsions among the molecules of the soft iron cause the poles to turn again in various directions, and thus to neutralize one another's action. The rod, therefore, no longer appears a magnet.

In the case of steel, which possesses greater molecular rigidity, greater difficulty is found in causing the molecules to set themselves with one class of poles pointing in one direction; but when the poles have once set themselves in this way, they retain their relative positions for a long time. For this reason, the steel remains permanently a magnet, while the soft iron possesses magnetic properties only while under the direct influence of the inducing magnet.

Steel is usually magnetized in one of the following ways:—

6. Methods of Magnetization.

1. Single Touch.

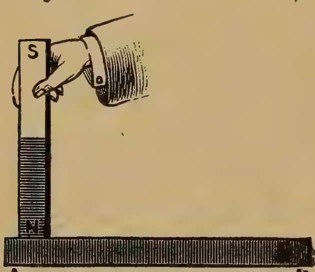


Fig. 116.

This method consists in rubbing the bar of steel to be magnetized repeatedly in the same direction with one pole of another magnet placed as shown in Fig. 116.

2. Double Touch.

The bar AB to be magnetized is usually supported on two magnets arranged as shown in Fig. 117, and is

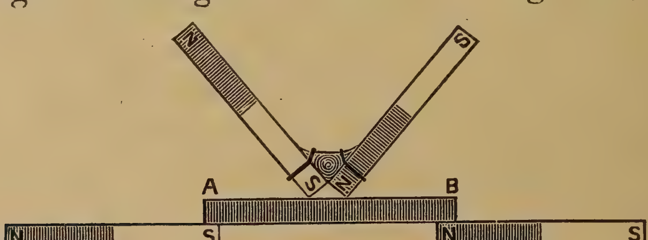


Fig. 117.

stroked first in one direction and then in the other by two bar magnets the opposite poles of which are kept at a constant distance from each other by means of a piece of wood, as shown in the figure.

3. Separate Touch.

The bar to be magnetized is supported on the opposite poles of two magnets as in the last case. The inducing magnets are placed as shown in Fig. 118, and are drawn

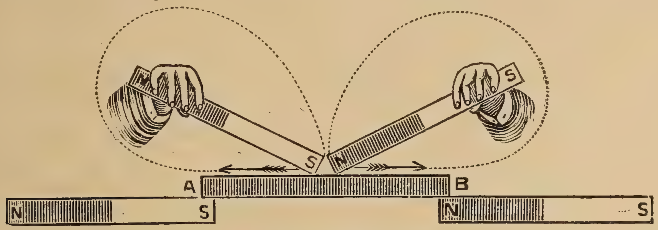


FIG. 118.

away from each other to the two ends of the bar, lifted up, carried back in a wide curve through the air, placed again at the middle, and again drawn away from each other to the two ends. This process is repeated several times.

Experiment 2.

Magnetize a needle by single touch. Prove that it is magnetic by rolling it in iron filings. Heat it red hot, allow it to cool, and again test its magnetic power.

1. What do you observe?
2. Explain the change.

7. Magnetic Field.

The space surrounding a magnet pervaded by the magnetic forces is called the field of the magnet. At every point in the field the magnetic force has a definite strength, depending, as we have seen, on the distance of the point from the poles.

8. Magnetic Lines of Force.

Experiment 3.

Lay a sheet of heavy paper or cardboard on a short bar magnet, and sprinkle iron filings over the paper by sifting them through a piece of muslin. Gently tap the paper, and observe the manner in which the filings arrange themselves under magnetic induction (Fig. 119).

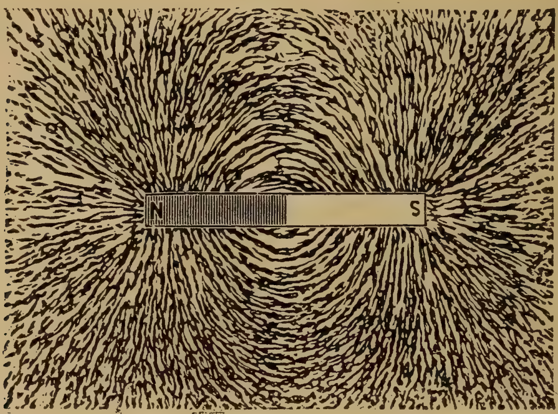


FIG. 119.

The experiment shows that magnetic induction takes place along certain lines. **The directions in the field of a magnet along which magnetic induction takes place are called the lines of magnetic induction, or lines of magnetic force.** They are commonly spoken of simply as "**lines of force.**"

Since each piece of iron takes its particular direction on account of the action of the two poles of the magnet upon it, the direction of the curve of the filings at any point represents the direction of the resultant of the forces at that point.

The lines of force can represent not only by their position the direction of the magnetic force, but also by their

number its intensity. Just as we speak of measuring the intensity of the illumination of a surface by the number of imaginary rays of light falling upon it, so we speak of estimating the strength of a part of a magnetic field in terms of the number of imaginary lines of magnetic force present in it. But it should be carefully borne in mind that, like the rays of light, the lines of force have no real existence. The actual forces do not act along a set number of lines, but pervade the whole magnetic field.

Experiment 4.

Repeat Experiment 3, placing a suspended magnetic needle in different positions over the card on which the iron filings are placed.

1. How does the magnetic needle in its different positions set itself with regard to the direction of the lines of force? Explain.

Experiment 5.

Magnetize a needle and suspend it, not by a stirrup, but by a silk fibre tied around it in such a position that it will rest horizontally. Now bring the needle within the field of a bar magnet, placing it at various points around, above, and below the magnet. Remembering that **the magnetic needle always tends to set itself parallel with the lines of force of the magnet,** note the direction of the lines of force at the different points at which the needle is placed (Fig. 120).

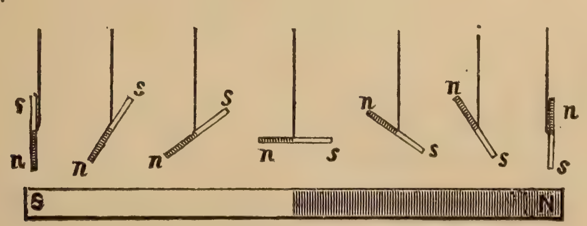


Fig. 120.

1. Do the lines of force all lie within one plane?

2. What is the direction of the lines of force in the axial line of the magnet?

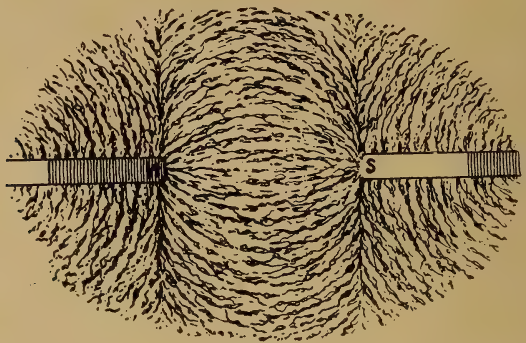


Fig. 121.

9. Superposition of Magnetic Fields.

Experiment 6.

Bring (1) a N-seeking pole of one magnet near a S-seeking pole of another (Fig. 121), (2) a N-seeking pole of one magnet near the N-seeking pole of another (Fig. 122). Place a card over the ends of the magnets in each case, sprinkle iron filings on it, and observe the curves formed when the card is gently tapped.

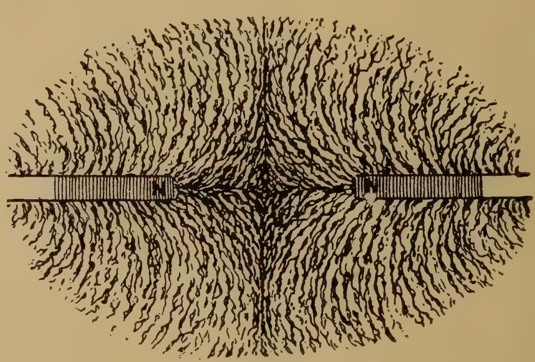


Fig. 122.

Experiment 7.

Repeat Experiment 10, placing the card over (1) a horse-shoe magnet, (2) two bar magnets placed parallel to each other, with like poles adjacent, and separated from each other about

2 cm., (3) two bar magnets placed parallel to each other and with unlike poles adjacent, (4) a horse-shoe magnet with its keeper on, (5) a bar magnet with a short bar of soft iron near one of its poles, (6) a soft iron ring with one pole of a powerful magnet near it.

1. Make drawings similar to Figs. 121 and 122, indicating the directions of the lines of force in the fields in each case.

2. What is the path of the greater number of the lines of force in (4), (5) and (6), through the air surrounding the poles near the soft iron or through the soft iron itself?

10. Permeability.

Experiment 8.

Interpose between a magnet and an iron tack, (1) a sheet of cardboard, (2) a pane of glass, (3) a thin wooden board, (4) a thick iron plate.

1. Does the magnet attract the tack through each of these bodies?

The magnetic forces act across all bodies which are not themselves magnetic.

The lines of force, instead of passing through a sheet of a magnetic substance into the air on the other side, pass laterally along it (Fig. 123), if it is sufficiently thick, because its **permeability** is many times that of the air.

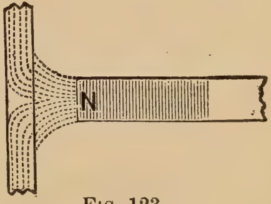


Fig. 123.

QUESTIONS.

1. A bar magnet is held vertically, and two equal straight pieces of soft iron wire hang downward from its lower end. The lower end of each of these wires can by itself hold up a small scrap of iron; but if the lower ends of both wires touch the same scrap of iron at the same time, they do not hold it up. What is the reason of this?

2. A pole of a magnet is brought within an inch of one side of a sphere of very hard steel, suspended from a string. It manifestly attracts the steel, but is not quite able to draw it into contact. A sphere of iron of the same weight is now substituted for the sphere of steel, and the magnet is found able to draw this new sphere quite up against itself. Explain this difference of action.

3. You have two similar rods, one of steel and the other of soft iron; you have also a bar magnet and some small iron nails. Describe some experiments which would enable you to distinguish the steel rod from the iron one.

4. If a compass-needle is deflected when a steel bar is brought near it, how can you find out whether the deflection is due to magnetism already possessed by the bar, or to the bar becoming magnetized by the compass-needle at the time of the experiment.

5. A bar magnet is laid upon a table, and a soft iron bar of about the same length as the magnet is hung horizontally just above it by a flexible string. What will be the effect on the soft iron bar if a second bar magnet is laid on the table and brought near the first, at right angles to it, and with its N-seeking pole pointing to the middle of the first magnet? Give a sketch explaining the action.

6. Three precisely similar magnets are placed vertically with their lower ends on a horizontal table. Iron filings are scattered over a plate of glass which rests on their upper ends, two of which are north poles and the third a south pole. Give a diagram showing the forms of the lines of force mapped out by the filings.

7. Why is less force required to pull a small iron rod away from the poles of a powerful horse-shoe magnet than would be required to pull a thick bar of iron away from the poles of the same magnet?

8. A magnet is placed near a compass-needle so as to pull the needle a little way round. If a thick sheet of soft iron is put between the magnet and the needle, what happens? Why?

9. You have three equal bar magnets without keepers. How would you arrange them so that, when not in use, they might retain their magnetism? Give a sketch.

10. A compass-needle is suspended inside a hollow ball of iron, and an outside magnet will not affect it. Explain.

11. A compass-needle and a straight strip of soft iron of the same length as the compass-needle are fastened together so as to be in contact with each other at both ends. Will the force which tends to make the combination point north and south be the same as that which would act on the compass-needle alone? Give reasons for your answer.

III.—The Earth's Magnetism.

Before proceeding to answer the following questions, review Section III., Chapter XXIV., pages 285–289, Part I.

QUESTIONS.

1. Given a magnet and the means of suspending it, how will you determine (1) the magnetic meridian, (2) in which direction **North** lies? It is assumed that you do not know which end of your magnet is a N-seeking and which a S-seeking pole.

2. A tall iron mast is situated a little in front of the compass in a wooden ship. Explain the nature of the compass error when the ship is sailing in an easterly direction (1) in the northern, (2) in the southern hemisphere.

3. If a compass were carried round the equator, would it point in the same direction at all places? If not, state, as nearly as you can, what changes would be observed in its behaviour during the journey.

4. The N-seeking poles of two equal and equally magnetized magnets are attached to the ends of a light bar of wood, so that the magnets are parallel to each other, and at right angles to the bar, with the S-seeking poles upon opposite sides of it. If the whole is suspended by a thread, so that the bar and the magnets lie in a horizontal plane, what position will the bar take up with respect to the magnetic meridian? Give reasons for your answer.

5. Describe the behaviour of a magnetic needle when a bar magnet, with its axis vertical, is moved up and down in its axial line, anywhere in the neighbourhood of the needle.

6. The beam of a balance is made of soft iron. When it is placed at right angles to the magnetic meridian, two equal weights placed in the opposite pans just balance. Will the weights still appear to be equal when the balance is turned so that the beam swings in the magnetic meridian? Give reasons for your answer.

7. If you were required to make a model to illustrate the magnetic properties of the earth by putting a bar magnet inside a ball of clay, show by a sketch how you would place the magnet, and explain how the magnetic properties of the model would answer to those of the earth.

8. A rod of iron, AB, held in a vertical position with the end B downward, is smartly tapped with a mallet. When turned into a horizontal position and brought near to a compass-needle, the end B repels the north pole of the needle at a distance of four inches, but attracts it when the distance is reduced to one inch. Explain this.

9. A large soft iron rod lies on a table in the magnetic meridian, and a dipping-needle is placed at some distance and at about the same level, (1) due south, (2) due north of it. How will the magnitude of the angle of dip be affected in each case? (Neglect any inductive action between the needle and the bar.)

10. Two bars of soft iron are so placed to the east and west of the N-seeking pole of a compass-needle that the needle still points north and south. If the iron to the east of the needle is replaced by a bar of hard steel of exactly the same size and shape as itself, will the direction in which the magnet points be altered? If so, in what direction will it move, and why?

11. Two equal bars of steel, after having been equally magnetized, are kept for some years in a vertical position, one (*a*) with its south-seeking pole upward, the other (*b*) with its north-seeking pole upward. The bars are so far apart that they do not act on each other; which of the two bars would you expect to find had kept its magnetism best, and why?

12. A bar of very soft iron is set vertically. How will its upper and its lower ends respectively affect a compass-needle? Would the result be the same at all points on the earth's surface as at this

latitude? If not, state generally how it would differ at different places?

13. Two bars of very soft iron are placed vertically, one east and the other west of the centre of a compass-needle, the lower end of the rod on the east and the upper end of the rod on the west being level with the compass. Describe and explain the effects on the compass.

14. A dipping-needle can oscillate in the magnetic meridian. A long bar of soft iron, held horizontally in a north and south direction, is brought near to it from the south. How is the inclination of the needle to the horizon affected as the distance between it and the bar is gradually diminished?

15. Suppose a magnetic needle to be carried in a circle of a few miles radius round the geographical north pole of the earth. How will the magnetic declination change during one complete circuit? How will it change if the needle is similarly carried round the magnetic pole?

CHAPTER XII.

THE ELECTRIC CURRENT.

I.—Potential.

1. An Electric Current.

Experiment 1.

Take a strip of zinc about 10 cm. long and 3 cm. wide and connect it with a strip of copper the same size by means of a wire about 50 cm. or more in length. Fill a tumbler about two-thirds full of water acidulated with about one-twelfth the quantity of sulphuric acid. Place the zinc and copper strips in the acidulated water, not allowing them to touch, and stretch the wire connecting them in a north and south direction (1) over, (2) under a compass-needle (Fig. 124).

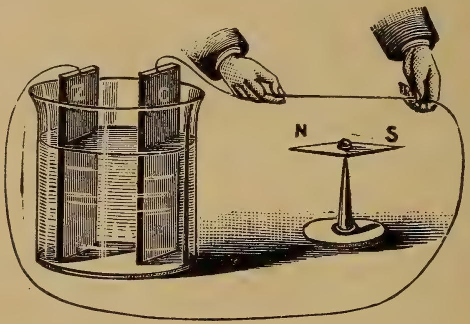


FIG. 124.

1. What change takes place in the direction of the needle when the wire is placed (1) over, (2) under the needle?

2. Does this change take place when the wire is above or below the needle, and the strips are removed from the liquid?

The wire evidently possesses new properties when the strips at its terminals are placed in the dilute acid. This result is said to be due to **electricity**.

Just as bodies possess a **thermal condition** called **temperature,** so they are regarded as possessing an **electrical condition,** which is called **potential**; and just as by the transference or the transformation of energy one body may be made to have a higher temperature than another, in consequence of which heat will pass from the one to the other when the two are connected by a thermal conductor, just so it is regarded as possible to cause one body to differ from another in electrical condition, in consequence of which an "**electric current**" will pass from one to the other, when the bodies are connected by an electrical conductor.

The **new properties of the wire** are said to be due to a **current of electricity, which passes through the wire, because a difference in the electrical condition, or potential, between zinc and copper is maintained when they are placed in the dilute acid.**

2. Potential Defined.

Potential may be provisionally defined, in general terms, as **that relatively electric condition of a conductor which determines the direction of the transfer of electricity.**

3. Potential, Temperature, and Level.

The current of electricity is said to pass from a point of high potential to a point of low potential, as heat passes from a point of high temperature to one of low temperature, or as liquid at a high level flows to a lower level; but the analogy between electricity and heat, or between electricity and a liquid, must not be pushed too far. It certainly is not molecular motion, and hence is

not transferred by an electrical conductor in the same way that heat is conducted; nor is it matter, as matter is usually defined, because it has no mass that can be measured. We are really ignorant of its nature.

4. Positively and Negatively Electrified Bodies.

For the purposes of comparison the earth is taken as a standard of potential, as the sea is taken as a standard for the comparison of levels. The earth's surface is regarded as zero potential, and a body of higher potential is spoken of as **positively electrified,** and a body of lower potential as **negatively electrified.** The terms **positive** and **negative** are also applied in a general way to any two related points in a conductor, the **positive** being **that from which,** and the **negative** that **to which, the current is flowing.**

5. Different Methods of Causing Bodies to Assume Different Potentials.

Difference in potential between bodies may be brought about in many ways. A vulcanite rod or a stick of sealing-wax after being rubbed with flannel differs in potential from the flannel. The terminals of a Holtz machine are made to differ in potential when the glass disc is revolved, and if the difference is sufficiently great a spark passes between them. Under certain conditions of the atmosphere one cloud differs from another, or from bodies on the earth, in potential, and as a result the two clouds, or the cloud and some body on the earth, may be connected by a flash of lightning.

These and similar methods of causing bodies to assume different potentials give rise to an interesting variety of phenomena; but we are concerned only with those methods which tend to keep the ends of a conducting wire at a constant difference of potential, and thus to produce a continuous electric current. This is usually accomplished either by means of Voltaic cells, as described in Art. 2, pages, 292-295, Part I., or by dynamos. See page 238.

II.—The Voltaic Cell.

6. Potential Series.

Experiment 1.

Connect the plates of a zinc-copper voltaic cell with the galvanoscope. Note the direction and the amount of the deflection of the needle.

Replace the copper plate by (1) a platinum one, (2) an iron one, (3) a silver one (a silver coin will answer), (4) a carbon one (a piece of an electric light carbon will answer).

1. Is the direction of the deflection of the needle the same in each case? If so, what does this indicate?

2. Is the strength of the current the same in each case?

3. If not, how can the difference be accounted for?

To answer the last question, consider the case of the zinc-copper and the zinc-platinum cells.

1. When the plates are the same size and kept the same distance apart, which gives the stronger current?

2. Which circuit do you believe will offer the greater resistance to the current?

3. Can you, therefore, account for the difference in current strength by difference in resistance?

4. If not, on what other theory would it be possible to account for it?

Experiment 2.

Connect the plates of a zinc-iron cell with the galvanoscope. Note the direction of the deflection of the needle. Now replace the zinc plate by a carbon one, and note the direction of the deflection of the needle.

1. Does the current now flow in the same direction as before?

2. If not, how can you account for the difference in direction?

The preceding two experiments show that **the difference in potential between different pairs of plates immersed in dilute sulphuric acid is different.** The potential of zinc is higher than that of iron, and the current flows from the zinc to the iron through the liquid, and from the iron to the zinc through the external circuit. When the zinc is replaced by carbon, the direction of the current is reversed. Thus showing that while zinc when immersed in dilute sulphuric acid is higher in potential than either iron or carbon, iron is higher in potential than carbon under the same conditions.

It is possible by performing experiments similar to the above to arrange different substances in a series in the order of their potentials when immersed in the same exciting fluid. Such a series is called a **potential, or electromotive series.**

Arrange the following substances in order, so that any two being chosen and connected by a conductor a current will flow from the latter to the former through the conductor when they are partially immersed in dilute sulphuric acid; carbon, copper, iron, lead, platinum, silver, tin, zinc.

7. Current and Potential-Difference.

The experiments also indicate that the **strength of the current** passing through the conductor joining the plates **depends not only upon the resistance in the circuit, but also upon the potential-difference between the plates.**

8. Electromotive-Force.

The term **electromotive-force**, or E.M.F., is applied to that which tends to produce a transfer of electricity. In the case of the battery current, the E.M.F. is the result of the potential-difference between the plates. Just as the difference in level in two tanks connected by a pipe causes a pressure which produces a transfer of water through the pipe, so a difference in potential is regarded as producing electromotive-force which causes a transfer of electricity through a conductor joining bodies of different potentials; and just as pressure can be estimated in terms of difference of level, for example when we say that the air pressure equals 30 inches of mercury, so electromotive-force may be measured in terms of potential-difference, because it is proportional to it.

The unit electromotive-force is the volt, which is the E.M.F. of a cell of which the potential-difference between the plates is nearly the same as between zinc and copper immersed in diluted sulphuric acid. A more exact definition of the unit will be given at a later stage.

9. Local Action.

Experiment 3.

Obtain, if possible, a piece of chemically pure zinc. Immerse it in dilute sulphuric acid. Also immerse in the acid a piece of ordinary commercial zinc.

What difference is observed in the chemical action between the acid and the two pieces of zinc?

Experiment 4.

Amalgamate a piece of commercial zinc by first dipping it in dilute sulphuric acid to clean it, and then dropping a few drops of mercury on it, and spreading the mercury over its surface by rubbing with a rag or brush.

Immerse the amalgamated zinc in dilute sulphuric acid.

1. Is there any chemical action between the zinc and the acid?

2. Can the amalgamated zinc be used with copper to form a zinc-copper cell?

To answer this question, connect it and a copper plate with the galvanoscope, and partially immerse the plates in dilute sulphuric acid.

1. Does the galvanoscope indicate a current?

2. Does the hydrogen appear as usual at the copper plate?

3. Does the zinc waste away (1) when not connected with the copper plate, (2) when connected with the copper plate? Find out by weighing.

The fact that the commercial zinc wastes away in the dilute sulphuric acid, while the pure zinc and the amalgamated zinc do not, is explained on the theory *that there is a difference in potential between the zinc and its impurities in consequence of which electric currents are set up between the zinc and the impurities in electrical contact with it.* The zinc then enters into combination with the acid when unconnected with any other plate. Such currents are called **local currents**, and the action is called **local action.**

Since a plate of ordinary zinc wastes away in a cell even when unconnected with any other plate without

any useful work being done, a plate of amalgamated zinc is commonly used for this purpose. When the zinc is amalgamated the mercury dissolves the pure zinc on the surface, forming a clean uniform layer of pasty zinc amalgam, and the zinc is acted upon by the acid only when it is connected by a conductor with another plate whose potential is different. As the zinc of the amalgam then combines with the acid, the mercury takes up more of the zinc, and the impurities float out into the fluid. Thus a homogeneous surface remains always exposed to the acid.

Why is chemically pure zinc not used in cells instead of amalgamated plates?

10. Polarization.

Experiment 5.

Connect the plates of a zinc-copper cell with the galvanoscope, allow the cell to stand for a few minutes and observe the changes in (1) the appearance of the surface of the copper, (2) the deflection of the needle of the galvanoscope.

1. What evidence have you that the strength of the current becomes weaker the longer the cell stands?

2. What change in the appearance of the copper plate accompanies the weakening of the current?

3. Is there any connection between the change at the surface of the copper plate and the weakening of the current?

To answer this question, remove the copper plate from the liquid, brush off all bubbles and replace it.

Is the current strength increased?

When, through a deposition of a film of hydrogen on the negative plate of a cell, the current becomes feeble, the cell is said to be **polarized.**

11. How Does the Film of Hydrogen on the Copper Plate Cause the Weakening of the Current?

To partially answer this question perform the following experiment:—

Experiment 6.

Place three plates in dilute sulphuric acid, two copper plates, C_1 and C_2, and a zinc plate, Z (Fig. 125). Connect the

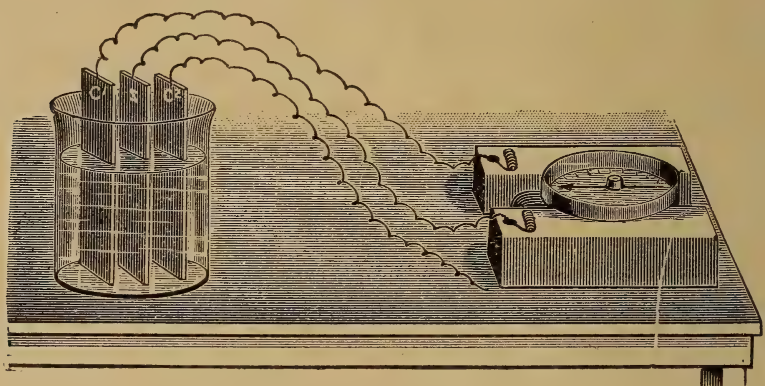


FIG. 125.

two copper plates with the galvanoscope, using the mercury cups so that the connections can be made and unmade rapidly.

Does the galvanoscope indicate a current?

Leaving C_1 connected with the galvanoscope, disconnect C_2 and connect the zinc plate with a mercury cup. Allow the cell to stand for a few minutes until C_1 becomes covered with a film of hydrogen, and the current grows weak. Now disconnect the zinc plate and at once connect the two copper plates with the galvanoscope as at first.

1. Does the galvanoscope now indicate a current?

2. If so, does it flow in the same direction as the current given by Z and C_1?

3. Which is of the higher potential, C_1 or C_2?

4. Does the film of hydrogen on the copper plate, therefore, increase or decrease the difference in potential between the copper plate and the zinc plate?

5. What effect will this change in potential have on the strength of the current?

The adhesion of the hydrogen to the copper plate weakens the current in two ways.

1. **By decreasing the potential-difference between the zinc and the copper plate**; because, as was shown in Experiment 4, the copper plate when covered with the film of hydrogen, is higher in potential than the clean copper plate.

2. **By increasing the internal resistance of the cell,** because the film of gas is a very bad conductor.

12. Methods of Preventing Polarization.

Voltaic cells differ from one another mainly in the remedies provided to prevent polarization. These are numerous, but may be classified as follows:—

1. **By mechanical means**, that is, by freeing the bubbles of gas from the plate in some mechanical way. Various methods have been proposed, such as keeping the plates in motion, agitating the fluid, etc.; but the only one which has come into practical use is that adopted in the Smee cell.

2. **By chemical means**, that is, by the use of some substance in the cell which will combine chemically with the hydrogen while it is in the nascent state, and thus prevent its appearance on the negative plate. This is usually a powerful oxidizing agent. The ones most commonly employed are bichromate of potassium, and nitric acid.

This method of preventing polarization is adopted in the following common cells:—

Grenet, Grove's, Bunsen's, and Leclanché's.

3. **By Electro-Chemical means,** that is, by employing such plates and such fluids that, not hydrogen, but the same substance as that of which the negative plate is composed, will be deposited on this plate by the action of the current. No change in potential in the plate will then be produced. The negative plate in cells of this class is usually copper. The more common forms are the Gravity cell and Daniell's cell.

13.—Common Voltaic Cells.

1. Smee's Cell.

Construction.

Fig. 126 shows the construction of Smee's cell. It consists of a silver plate, covered with finely-divided

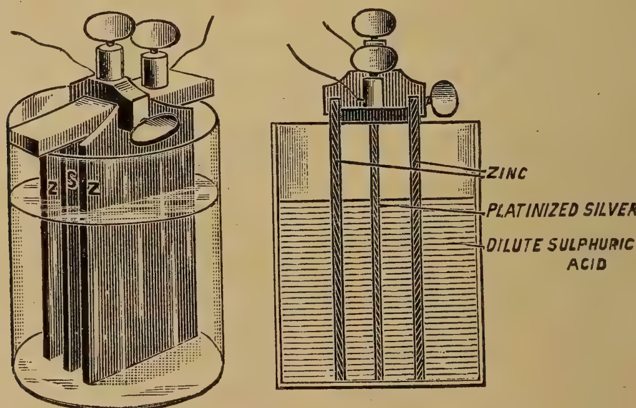


FIG. 126.

platinum, and two connected zinc plates immersed in dilute sulphuric acid.

Chemical Action.

When the plates are connected by a conductor, the zinc displaces the hydrogen of the sulphuric acid, forming zinc sulphate. The liberated hydrogen escapes freely from the numerous sharp points on the platinized silver plate. Polarization is thus prevented for a time.

Current, Etc.

The E.M.F. of the cell is at first nearly one volt, but decreases considerably after a few minutes' use. The current is, therefore, not constant.

2.—Grenet or Bichromate Cell.

Construction.

Fig. 127 shows the construction of the Grenet or Bichromate cell. It consists of two connected carbon plates and a zinc plate between them, immersed in a

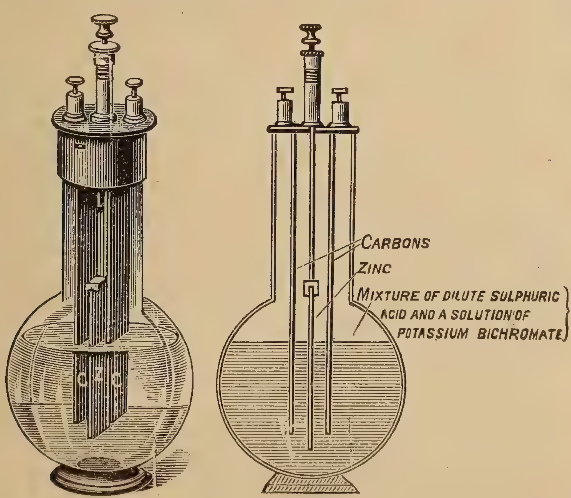


FIG. 127.

solution of potassic bichromate in water mixed with sulphuric acid. The zinc plate is usually attached to a rod so that it can be raised out of the fluid when not in use.

Chemical Action.

The chemical actions in the cell are somewhat complicated, but the following are the leading ones.

The sulphuric acid acts upon the potassic bichromate, forming chromic acid. When the circuit is completed, the zinc displaces the hydrogen of the sulphuric acid, forming zinc sulphate, and the hydrogen in the nascent state reduces the chromic acid. Polarization is thus prevented.

Current, Etc.

The E.M.F. remains constant at about 2 volts for a short time, but soon decreases rapidly. The cell is consequently capable of giving a strong current for a few minutes.

3. Grove's Cell.

Construction.

The construction of Grove's cell is shown in Fig. 128. It consists of a zinc plate immersed in dilute sulphuric

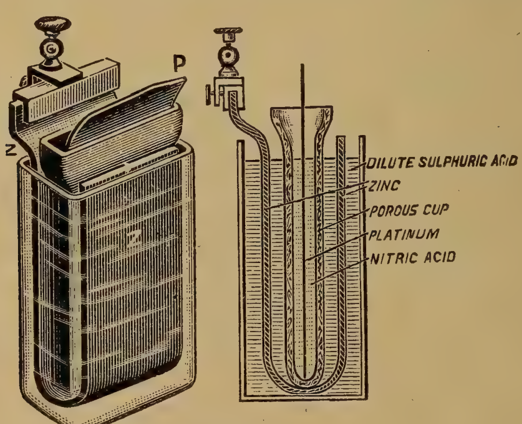


FIG. 128.

acid in an outer vessel, and a platinum plate immersed in nitric acid placed in an inner porous cup.

Chemical Action.

The zinc displaces the hydrogen of the sulphuric acid, forming zinc sulphate, and the nascent hydrogen reduces the nitric acid, thus preventing polarization.

Current, Etc.

The E.M.F. of the cell is about 1.9 volts, and remains nearly constant for some time. One of these cells will furnish an energetic continuous current for three or four hours.

4. Bunsen's Cell.

Bunsen's cell differs from Grove's cell in substituting a carbon plate for a platinum one. Fig. 129 shows a common form of it.

The chemical action is the same as in the Grove cell. The character of the current given by it is also very much the same, the E.M.F. being slightly higher.

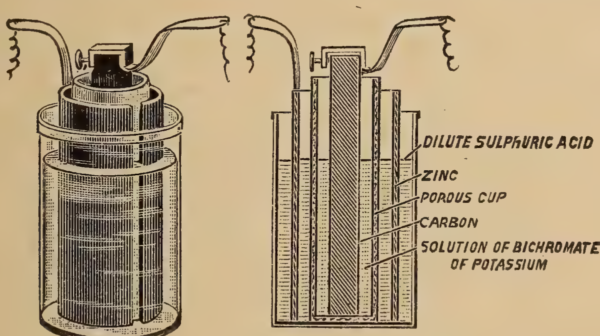


FIG. 129.

5. Leclanché Cell.

Construction.

The construction of the Leclanché cell is shown in Fig. 130.

It consists of a zinc rod immersed in a solution of ammonic chloride in an outer vessel and a carbon plate

surrounded by a mixture of small pieces of carbon and powdered manganese dioxide in an inner porous cup.

Chemical Action.

The solution of ammonic chloride acts upon the zinc, forming a double chloride of zinc and ammonium, and liberating ammonia and hydrogen. The hydrogen is oxidized by the manganese dioxide.

As the reduction of the manganese dioxide goes on very slowly, the cell soon becomes polarized, but recovers itself when allowed to stand for a few minutes. The E.M.F. is about 1.4 volts at first. As the zinc does not waste away when the circuit is not complete, it does not require renewing for several months, when used intermittently for a minute or two at a time. It is, consequently, specially adapted for use with electric bells, telephones, etc.

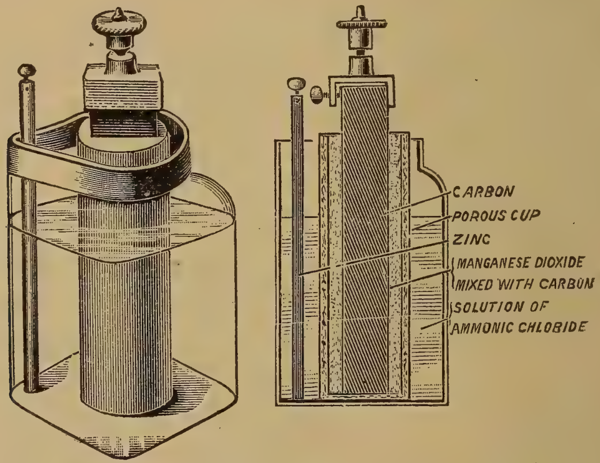


FIG. 130.

6. Dry Cells.

Dry cells are now commonly used in open circuit work for electric bells, telephones, gas-engine ignition,

etc. There is a great variety of forms of these cells, but most of them are modifications of the Leclanché cell, in which a paste is substituted for the fluid.

A paste with the following constituents makes a very effective cell :—

Charcoal - - -	3 parts	by weight.
Graphite - - - -	1 part	" "
Manganese dioxide - -	3 parts	" "
Slaked lime - - - -	1 part	" "
Arsenic trioxide - - -	1 "	" "
Mixture of glucose and starch	1 "	" "

These should be intimately mixed when dry, and then worked into a smooth paste, with equal parts of a saturated solution of ammonic chloride, and a similar solution of common salt, to which one-tenth by volume of a saturated solution of corrosive sublimate and one-tenth by volume of hydrochloric acid have been added.

The carbon plate is supported at the centre of a zinc vessel, which acts as the positive plate, and the unoccupied space is packed with the paste. The vessel is then sealed with a non-conducting cement, leaving a small aperture for the escape of gas.

7.—Gravity Cell.

Construction.

Fig. 131 shows a common form of the cell. A copper plate is placed at the bottom of a vessel, and a zinc plate suspended near the top. Crystals of copper sulphate are placed at the bottom of the vessel around the copper plate, and the vessel is nearly filled with water. The liquid at the lower part of the vessel is, therefore, a saturated solution of copper sulphate.

Chemical Action.

When a little dilute sulphuric acid is added, the zinc displaces the hydrogen of the acid, forming zinc sulphate; the displaced hydrogen in turn displaces the copper of the copper sulphate, forming more sulphuric acid, and copper instead of the hydrogen is deposited on the copper plate. The zinc displaces the hydrogen of the sulphuric acid formed, and so on; hence the zinc wastes away, copper is deposited on the copper plate and zinc sulphate dissolves in the water. The zinc sulphate solution, being much less dense than the copper sulphate solution floats on the top of it, leaving a sharp line of demarkation between the solutions when the cell is undisturbed.

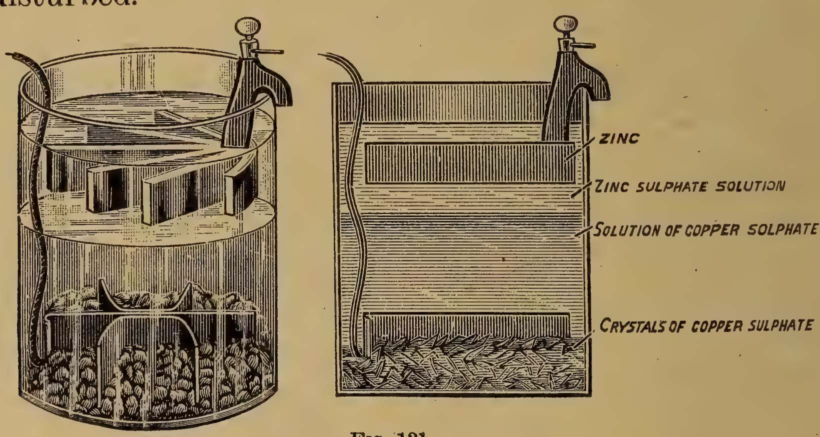


Fig. 131.

Current, Etc.

Since nothing but copper is deposited on the copper plate, the cell is never polarized; consequently it is capable of giving a continuous current for an indefinite period, if the materials are renewed at regular intervals. For this reason it is adapted for use with telegraph instruments, or for other closed circuit work.

The E.M.F. is about 1.07 volts.

8. Daniell's Cell.

Fig. 132 shows the construction of the Daniell cell. It consists of a copper plate, which is frequently the outer vessel, immersed in a concentrated solution of copper sulphate, and a zinc plate immersed in dilute sulphuric acid in an inner porous vessel.

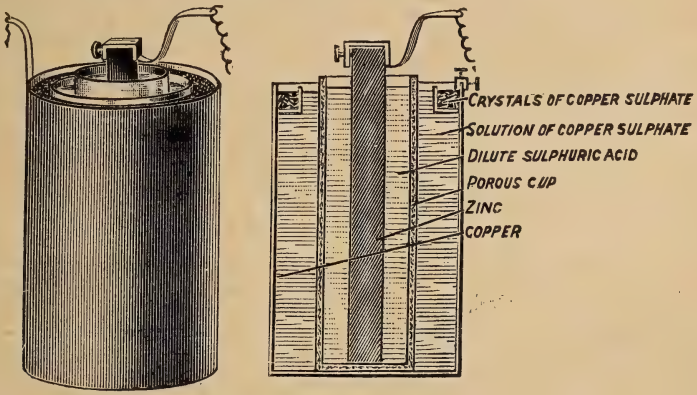


FIG. 132.

Chemical Action.

The zinc displaces the hydrogen forming zinc sulphate, and the displaced hydrogen in turn displaces the copper from the copper sulphate, forming sulphuric acid; and the displaced copper, instead of the hydrogen, is deposited on the copper plate. Hence polarization is altogether done away with.

Current, Etc.

Since the cell is not subject to polarization, it, like the Gravity cell, may be used for continuous closed circuit work. Its E.M.F. is the same as that of the Gravity cell.

1. How would the action of a Daniell's cell be modified if the solution of copper sulphate were replaced by dilute sulphuric acid?

2. The platinum plate of a Grove's cell is connected with the copper plate of a Daniell's cell. Would there be a current if the zinc plates were also connected, and if so, in which direction would it flow? What reasons have you for your answer?

14. Uses of Cells.

Dynamos and storage cells have altogether displaced primary cells whenever a powerful current is required for commercial purposes.

Some form of the Gravity or the Daniell cell is generally employed for working telegraph instruments, but the larger companies are introducing dynamo and storage battery plants for this purpose. The Leclanché cell is used on telephone circuits, and for ringing electric call-bells, gongs, etc.

Bichromate or Bunsen cells are frequently used in the laboratory for illustrating the different effects of the electric current, but some of the better forms of dry cells are much more convenient for this purpose. A battery of four such cells will be found sufficient for most of the experiments requiring an electric current described in this book.

Where a direct current is available in the laboratory for charging storage cells, these will be found to be more reliable than the dry cells. Since storage cells differ widely in efficiency, only those made by reliable companies for actual commercial work should be purchased.

The plates of the storage battery should be placed in glass cells, which should remain stationary in some convenient place, and wires should be carried from it to the points where the current is to be used.

The cells should have a capacity of not less than 50 ampere-hours.

CHAPTER XIII.

THE CHEMICAL EFFECTS OF THE ELECTRIC CURRENT.

I.—Electrolysis.

1. Electrolysis of Water.

Repeat Experiment 2, page 305, Part I.

2. Electrolysis of Hydrochloric Acid.

Experiment 1.

Arrange apparatus as shown in Fig. 133.

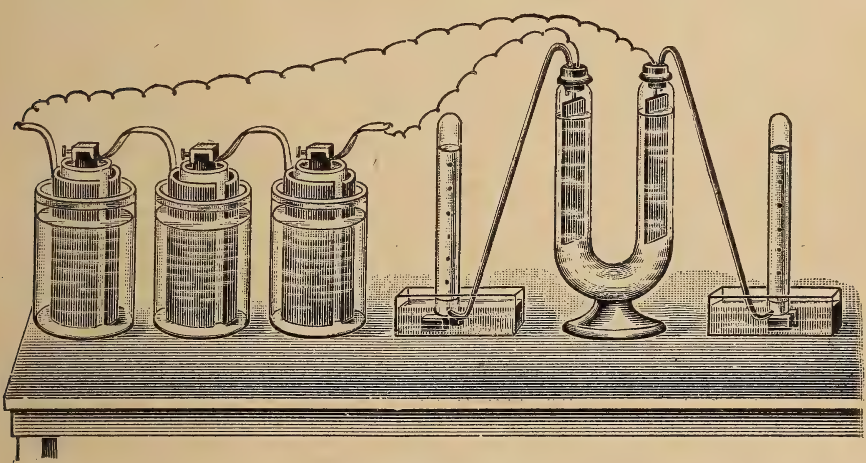


FIG. 133.

The U-tube is filled nearly full of hydrochloric acid. The wires are passed through the perforated corks, and a small pencil or plate of carbon, to serve as an electrode, is attached to the end of each. The corks are then inserted, and the other ends of the wires connected with the poles of the battery. If gases are liberated at the electrodes, they will pass up through the glass tubes passing through the corks, and may be collected in small test-tubes by the displacement of hot water or a saturated solution of common salt.

1. Describe what takes place when the circuit is completed.

Observe the colour of the gases liberated. Test each with a burning splinter.

2. What is the anion, and what the cation?

3. Electrolysis of Salts.

Experiment 2.

Repeat Experiment 1, attaching platinum strips, instead of carbon pencils, to the ends of the wires, and filling the U-tube with a solution of copper sulphate. Collect the gas which is liberated at one of the electrodes by the displacement of water.

1. What is deposited on the cathode?

2. What gas is liberated at the anode? To answer this question insert a splinter, at the end of which is a glowing ember, into the test-tube when filled with the gas.

Experiment 3.

Repeat Experiment 2, allow the current to pass until a deposit is formed on the cathode and then reverse the direction of the current by changing the wires at the poles of the cell.

1. Upon which pole is the deposit now formed?

2. Does the deposit remain on the plate which was at first the cathode?

3. Is gas liberated at either electrode while the change in the deposit is taking place? If not, explain.

Experiment 4.

Weigh two strips of copper, attach each to the pole of a voltaic cell, and, without allowing them to touch, dip them into a solution of copper sulphate.

Is any change observed to take place at either plate? If so, describe it.

When the strips have remained a few minutes in the solution, remove them, and, remembering which was the anode and which the cathode, weigh them again.

1. What change has taken place in the weight of (1) the anode, (2) the cathode?

2. How do you account for these changes?

Experiment 5.

Set up apparatus as for the electrolysis of water (Fig. 246, page 305, Part I.) Fill the vessel and test-tubes with a strong solution of common salt (NaCl), to which has been added sufficient red litmus solution to colour it distinctly.

1. What gases fill the tubes?

2. Account for the change in colour around one of the electrodes.

Experiment 6.

Repeat the last experiment, using a solution of sodium sulphate instead of sodium chloride, and making the litmus purple in colour by exact neutralization.

1. What gases are now liberated?

2. Account for the change in colour around each electrode.

4. Summary.

The preceding experiments show:

1. That electrolytes are—

(*a*) Dilute acids.

(*b*) Solutions of metallic salts. Certain fused salts are also capable of electrical decomposition.

2. That when electrolysis takes place the substances resulting from the decomposition of the electrolyte are found at the electrodes. **Hydrogen and the metals are cations,** while **oxygen, chlorine, iodine,** etc., and **electro-negative radicals** are **anions.**

3. That in most cases of electrical decomposition, secondary actions, depending on the chemical affinities of the elements involved, take place. For example :—

(*a*) In Experiment 2, the radical sulphion (SO_4) combines with the hydrogen of the water, forming sulphuric acid (H_2SO_4) and liberating oxygen.

(*b*) In Experiment 4, the radical sulphion (SO_4) combines with the copper of the anode, forming more of the copper sulphate ($CuSO_4$).

(*c*) In Experiment 5, the sodium re-acts upon the water forming sodium hydroxide and liberating hydrogen.

(*d*) Even in the case of the electrolysis of water, it is probable that the radical sulphion (SO_4) of the sulphuric acid combines with the hydrogen of the water, thus liberating the oxygen and forming more of the acid. The quantity of the acid, therefore, remains constant, and the water only is decomposed.

1. What are the chemical changes which take place in Experiment 6?

2. Write equations representing the chemical actions which take place in Experiments 3–5.

5. Theory of Electrolysis.

The following is the theory at present most commonly accepted as explaining the phenomena of electrolysis :—

1. An electrolytic salt or acid when in solution, or when melted, becomes more or less completely dissociated, the respective parts into which its molecules divide being known as ions. For example the ions of HCl are H. (atoms) and Cl (atoms); of $CuSO_4$, Cu (atoms) and SO_4.

2. These ions are supposed to be electrically charged and to wander about through the solution.

3. When the electrodes are connected with the poles of a battery or dynamo, the positively charged ions (cations) are attracted and move towards the cathode, or negatively charged electrode. When they reach it they part with their positive charges, thereby ceasing to be ions and becoming as ordinary atoms the constitutents of molecules. Similarly the negatively charged ions (anions) move towards the anode, where they part with their negative charges.

4. This migration of positively and negatively charged ions constitutes the current in the electrolyte. The electrolyte is, therefore, not a conductor in the same sense as the wires of the external circuit. The positive charges which the cations bring to the cathode tends to diminish the charge of the cathode, while the negative charges carried by the anions tends to diminish the charge of the anode; but a constant difference of potential between the electrodes is kept up by the current maintained in the external conductor by the battery or dynamo.

To illustrate this theory, take the case of the electrolysis of a solution of common salt.

When the salt is dissolved in water, the molecules are dissociated and the ions, atoms of the sodium bearing positive, and atoms of chlorine bearing negative, charges of electricity, wander about through the water. When the electrodes of the electrolytic cell are connected with the poles of a battery or dynamo, the positively charged sodium atoms are attracted to the negatively charged cathode, where they part with their positive charges, and re-act upon the water forming sodium hydroxide and liberating hydrogen. Simultaneously the negatively

charged chlorine atoms move to the anode, part with their negative charges and combine in pairs to form molecules of chlorine.

II.—Practical Applications of the Chemical Effect of the Current.

1. Electroplating.

The deposition of a metal from a salt by means of an electric current is taken advantage of for covering one metal with a thin layer of another. The process is known as electroplating.

The metallic object to be plated is connected by a conductor with the negative pole of a battery or dynamo, and immersed in a bath containing a solution of a salt of the metal with which it is to be plated. A plate of this metal is also immersed in the bath and is connected by a conductor with the positive pole of the battery or dynamo; that is, the object to be plated is made the cathode, the metal with which it is to be plated is made the anode. and the electrolyte is a salt of this metal. When the current passes through the solution from the plate to the object, the salt is decomposed and the metal is deposited on the object; but as the radical of the salt combines with the metal forming the anode, the strength of the solution remains constant. The metal is thus transferred from the plate to the object.

For copper plating, the bath is usually a solution of copper sulphate; for gold and silver plating, a solution of cyanides of these metals is commonly used.

Fig. 134 shows a bath and the connections for silver plating.

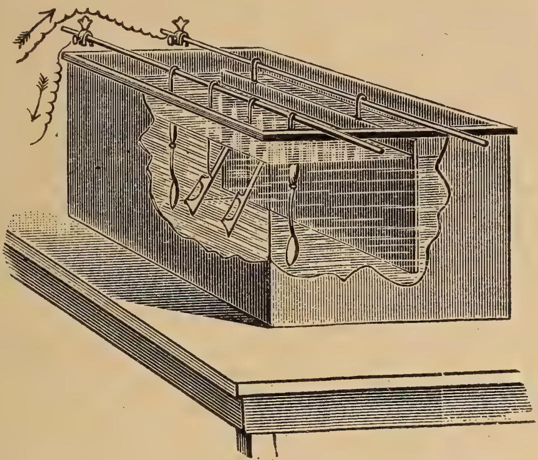


FIG. 134.

2. Electrotyping.

Books are now usually printed from electrotype plates instead of from type. These are made as follows:—

An impression of the type is made in a wax mould. This is covered with powdered plumbago to provide a conducting service upon which the metal can be deposited. The mould is flowed with a solution of copper sulphate, and iron filings are sprinkled over it. The iron displaces copper from the sulphate, and the plumbago surface is thus covered with a thin film of copper. The iron filings are washed off, and the mould immersed in a bath of nearly concentrated copper sulphate solution slightly acidulated with sulphuric acid. The copper surface is then connected by a conductor with the negative pole of a battery or dynamo, and a copper plate which is connected with the positive pole is immersed in the bath.

When the current passes, the copper sulphate is decomposed and a layer of copper is deposited uniformly on the mould, while the copper anode combines with the sulphion (SO_4) groups to form more of the copper sulphate. When the layer of copper has become sufficiently thick it is removed from the bath, backed with melted type-metal and mounted on a wooden block. The face is an exact reproduction of the type or engraving.

3.—Reduction of Ores.—Electricity applied in Manufactures.

Electrical decomposition is sometimes resorted to for reducing metals from their ores. A soluble or fusible salt is formed by the action of chemical re-agents, and the metal is deposited from this by electrolysis.

For example, copper is now produced on a large scale by electro-deposition. Aluminium is also reduced in large quantities from a fused mixture of electrolytes.

A current of electricity is now frequently employed for preparing chemical products for commercial purposes. Caustic soda, chlorate of potassium, and bleaching liquors are manufactured extensively by electrolytic processes.

4. Secondary or Storage Cells.

6. Polarization of Electrodes.

Experiment 1.

Connect by means of wires two platinum strips with the poles of two Bichromate or Bunsen cells, placing a galvanoscope in the circuit. Keep the strips from touching, and immerse them in water acidulated with sulphuric acid. Observe the direction of the deflection of the needle of the

galvanoscope, and as soon as the gases are given off freely from the strips, disconnect the wires from the poles of the battery, and at once join them together, as shown in Fig. 135.

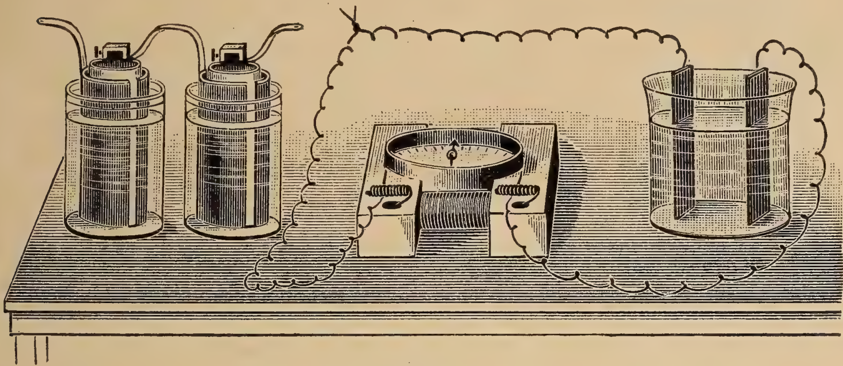


FIG. 135.

1. What evidence have you that a current of electricity flows through the wires when they are disconnected from the battery and joined?

2. Does the current flow in the same direction as the battery current, or in a direction opposite to it?

3. How long does the current continue to flow?

When a film of hydrogen surrounds one platinum strip in the dilute sulphuric acid and a film of oxygen the other, there is a difference in potential between the strips, which causes a current to flow from one to the other when they are joined by a conductor. The electrodes are then said to be **polarized.**

As the hydrogen is of higher potential than the oxygen, the direction of the current in the conductor joining the electrodes will be opposite to the direction of the current which deposited the oxygen and hydrogen. Hence, in order to overcome this difference in potential and to decompose water, the E.M.F. of the battery used

must be greater than the opposite E.M.F. caused by this potential-difference between the electrodes. This is about 1.47 volts.

Experiment 2.

Repeat the last experiment, using two lead strips instead of platinum ones. They should be an inch or more in width.

Allow the current to pass from one strip to the other through the dilute acid for a few minutes. Observe the direction of the deflection of the needle of the galvanoscope and any changes which take place in the appearance of the surface of either strip. Disconnect the wires from the poles of the battery, and join their ends as in the last experiment. Again observe the direction of the deflection of the needle of the galvanoscope, and any changes in the appearance of the surface of either strip of lead.

1. What changes are observed to take place in either lead strip (1) when the battery is in the circuit, (2) when the battery is disconnected and the ends of the wires joined?

2. What is the cause of the current which flows through the wires when the battery is disconnected and the circuit completed?

3. How does the direction of the battery current compare with that given by the lead strips immersed in the dilute acid?

4. Can the latter current be used to ring an electric bell? Try.

7. Secondary or Storage Cells.

The last experiment illustrates the principle of action of all secondary, or storage, cells.

When the current is passed through the dilute acid from one plate to the other the oxygen freed at the anode unites with the lead, forming an oxide of lead. The composition of the anode is thus made to differ from the cathode, and in consequence there is a difference in

potential between them, which causes a current to flow in the opposite direction when the plates are joined by a conductor.

This current will continue to flow until the plates become again alike in composition, and hence in potential.

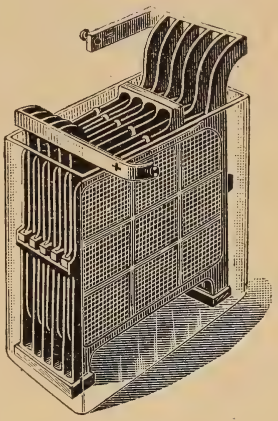


FIG. 136.

Instead of using solid lead plates, perforated plates, or "grids," made of lead or some alloy of lead, are frequently employed. The holes in the plates are filled with a paste of lead oxides, which form the "active material" (Fig. 136). When the plates are immersed in dilute sulphuric acid and the current passed through the cell, these oxides are changed into peroxide (PbO_2) in the positive plates and reduced to spongy lead in the negative.

The chemical changes which go on in the storage cell are very complex, and, to a certain extent, undetermined. The following equations represent approximately the re-actions which, according to the latest investigations, are believed to take place:

Charged cell PbO_2, xH_2, SO_4, yH_2O, Pb, equals

Discharged cell $PbSO_4$, $(x-2)$ H_2SO_4, $(y+2)$ H_2O, $PbSO_4$.

During the process of discharge both plates are converted into lead sulphate, and a part of the sulphuric acid disappears thus lowering the density of the electrolyte. When the cell is being charged the sulphion ions combine with lead sulphate and water to form the

lead peroxide and sulphuric acid, and the hydrogen ions re-act upon the lead sulphate forming spongy lead and sulphuric acid.

1. What transformations of energy take place in (1) charging a secondary cell, (2) discharging it.

2. Is anything "stored up" in a storage cell? If so, what?

5. Measurement of the Current—Voltameters.

8. Laws of Electrolysis.

Carefully repeated quantitative experiments have verified the following laws of electrolysis.

Law I.—**The amount of an ion liberated at an electrode in a given time is proportional to the strength of the current.**

Law II.—**The weights of the elements separated from an electrolyte by the same electric current are in the proportion of their chemical equivalents.**

These laws furnish a means of comparing the strength of one electric current with that of another, and hence of measuring a current when a unit current is adopted.

9. Unit Current.

The practical unit of current commonly adopted is the **ampere, which may be defined to be a current which deposits silver at the rate of 0.001118 grams per second.** The same current deposits per second 0.000328 grams of copper, and liberates 0.000010386 grams.

The weight of an element liberated in one second by a current of one ampere is called the **electro-chemical equivalent** of the element.

An electrolytic cell used for the purpose of comparing the strengths of different currents is called a **voltameter.**

10. Silver Voltameter.

The silver voltameter consists of a light platinum bowl partially filled with a solution of silver nitrate in which is suspended a silver disc. When the voltameter is placed in the circuit, the platinum bowl is made the cathode, the silver disc the anode, and the current to be measured is passed through the silver nitrate solution for a specified time. The silver disc is then removed, the solution of nitrate poured off, and the silver deposited in the bottom of the bowl washed, dried, and weighed. The rate in grams per second, at which it is deposited is then calculated, and this divided by 0.001118 gives the measure of the current in amperes, or

$$C = \frac{W}{t \times .001118}$$

when C is the measure of the current in amperes, and W is the weight of silver deposited by it in t seconds.

The current should not exceed one ampere for each six square inches of the surface of the electrodes.

11. Copper Voltameter.

The copper voltameter consists of two copper electrodes immersed in a solution of copper sulphate. The plate made the cathode is weighed, and the current to be measured is passed through the copper sulphate solution for a specified time. The cathode is then removed, washed, dried, and weighed. If W grams is the increase in weight in the cathode in t seconds.

$$C = \frac{W}{t \times .000328}$$

where C is the measure of the current in amperes.

The surface of each plate immersed in the copper sulphate solution should be at least two square inches for each ampere of current to be measured. Fig. 137 shows a common form of the instrument.

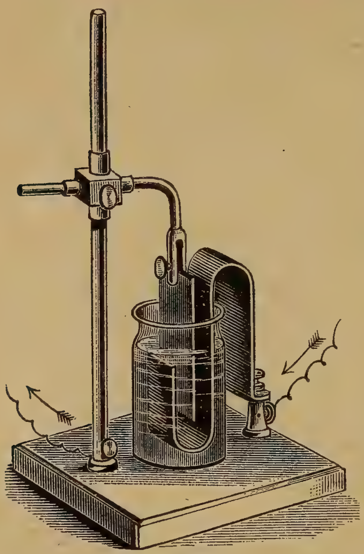


FIG. 137.

12. Water Voltameter.

The water, or hydrogen, voltameter consists of the apparatus used for the decomposition of water (Experiment 2, page 305, Part I). The vessel is filled with water acidulated with a few drops of sulphuric acid. A graduated tube is also filled with the water, and is inverted over the platinum strip made the cathode.

The current to be measured is passed through the water until the liquid in the tube stands on a level with the liquid in the vessel, and the time during which the current is passing is noted. The temperature of the gas and the barometric pressure are also noted. The volume of the hydrogen liberated is read from the graduated tube, reduced to standard temperature and pressure, and the mass corresponding to this volume calculated.

Then, if the current is passing for t seconds, and W grams is the weight of the hydrogen liberated,

$$C = \frac{W}{t \times .000010386}$$

where C is the measure of the current in amperes.

QUESTIONS.

1. Can a single Gravity cell be used to decompose water? If not, why?

2. When a plate of zinc and a plate of platinum connected by a wire are both dipped into the same vessel of dilute sulphuric acid, an electric current passes through the wire. State and account for the effect of moving one of the plates into a separate vessel of acid.

3. Two copper wires, one connected with one terminal of a voltaic battery and the other connected with the other terminal, dip side by side, but without touching each other, into a solution of sulphate of copper. What happens to the immersed part of each wire?

4. Plates of copper and platinum are dipped into a solution of copper sulphate, and a current is passed through the cell from the copper to the platinum. Describe the effects produced; also what happens when the current is reversed.

5. A vertical partition of porous earthenware is fitted into a tumbler, and dilute sulphuric acid is poured into each compartment. Rods of common zinc and copper are placed respectively in the two compartments, and connected by a wire. State what will be observed with regard to the evolution of gas, and how the observed phenomena will be modified when copper sulphate is poured into the compartment containing the copper rod.

6. A piece of zinc and a piece of copper are each carefully weighed; they are then connected by a copper wire and dipped side by side into dilute sulphuric acid contained in an earthenware jar. After, say, half an hour, the pieces of zinc and copper are taken out of the acid, washed and dried, and weighed again. Would the weights be the same as at first? If not, how, and why, would they differ?

7. A vessel containing a solution of salt, coloured with a little litmus or indigo, is divided into two parts by a partition formed by stitching together several layers of blotting paper. The wires coming from the poles of a Grove's battery are dipped into the liquid on opposite sides of this partition. On one side the colour

is observed to disappear. Explain its disappearance, and mention the pole of the battery from which the wire that destroys the colour proceeds.

8. The same current is passed through three electrolytic cells, the first containing acidulated water, the second a solution of copper sulphate, and the third a solution of silver nitrate. What weight of hydrogen and what weight of oxygen will be liberated in the first cell, and what weight of copper deposited on the cathode of the second cell when 11.18 grams of silver are deposited on the cathode of the third cell?

9. Is there polarization of the electrodes in (1) the water voltameter, (2) the copper voltameter, (3) the silver voltameter? Give reasons for your answer.

10. Obtain two copper plates, make a copper voltameter, and measure with it the current given by any cell.

CHAPTER XIV.

THE MAGNETIC EFFECTS OF THE CURRENT.

I.—Electricity and Magnetism.

1. Magnetic Field Due to an Electric Current.

Experiment 1.

Pass a strong current from a battery* through a copper wire, dip the wire into iron filings, and lift it out.

1. What is observed?

Break the circuit.

2. What now takes place? Why?

Experiment 2.

Arrange apparatus as shown in Fig. 138. Drop a magnetized needle on the surface of the water near the vertical wire (See Experiment 1, page 89, Part I.), and connect the ends of the wire with the poles of a battery.

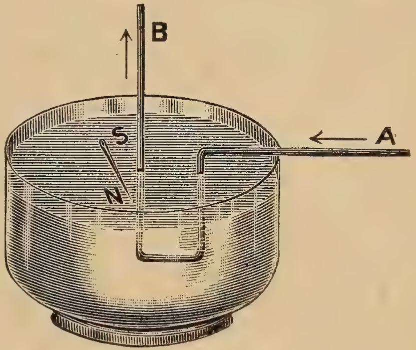


FIG. 138.

How did the needle set itself (*a*) before, (*b*) after the wire was connected with the battery?

Reverse the direction of the current.

How does the needle behave?

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* If a storage battery is used for experiments of this class, care should be taken to keep from "short-circuiting" it, that is, using it with a resistance so low that the battery discharges at too high a rate. To prevent this, a resistance coil should be permanently attached to one of the poles of the battery. A suitable coil of iron telegraph wire will answer well. The rate of discharge will depend upon the number and the size of the plates in the cell. The rate should be ascertained from the maker.

Experiment 3.

Pass a thick wire vertically through a hole in the centre of a card. Sprinkle iron filings from a muslin bag over the card, Fig. 139. Now connect the ends of the wire with the poles of a battery, and gently tap the card.

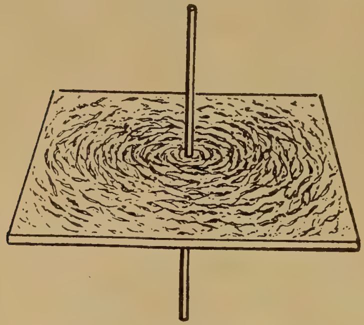

FIG. 139.

1. How do the iron filings arrange themselves around the wire?

2. What does this prove?

Experiment 4.

Repeat Experiment 1, page 150.

The above experiments show **that a wire through which an electric current is flowing is surrounded by a magnetic field, the lines of force of which pass in circles around it**; that is, the wire throughout its whole length is surrounded by a "sort of enveloping magnetic whirl." The poles of a magnetic needle placed in this field are apparently urged with equal force in opposite directions around the wire, and it, therefore, remains at a tangent to it.

Experiments 3 and 4 show that the direction in which each pole of the magnetic needle tends to turn around the wire depends on the direction of the current. If **we imagine a current to flow through a wire from an observer to the face of a clock, the N-seeking pole of a magnetic needle placed in its field tends to turn in the direction of the hands of the clock, while the S-seeking pole is urged in the opposite direction.** If there were but one pole to the magnet it would apparently revolve around the wire continuously.

2. Magnetic Field about a Circular Conductor.

Experiment 5.

Take a piece of copper wire, No. 16, and bend it into the form shown in Fig. 140, making the circle about 20 cm. in diameter. Suspend the wire by a long thread, and allow its ends to dip into mercury held in receptacles made in a wooden block of the form shown in the figure. The inner receptacle should be about 2 cm. in diameter and the outer one 2 cm. wide, with a space of 1 cm. of wood between them. Pass a current through the circular conductor by connecting the poles of a battery with the mercury in the receptacles. For convenience in making the connections the receptacles should be connected by **iron** wires with binding posts screwed into the block.

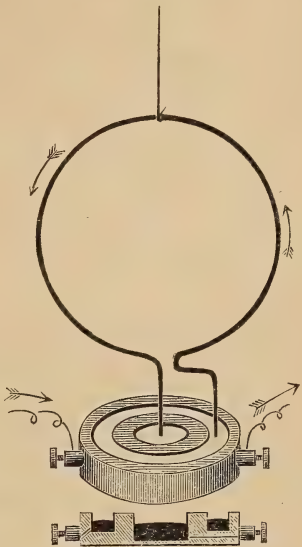

FIG. 140.

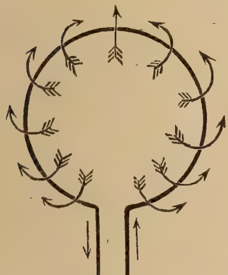

FIG. 141.

When the current is passing, bring a magnet near the face of the circular conductor.

What position relative to the poles of the magnet does the conductor take?

The experiment shows that a circular conductor acts as a disc magnet whose poles are its faces. The lines of force surround the conductor as shown in Fig. 141.

Which is (*a*) the N-seeking face, (*b*) the S-seeking face of the circular conductor (Figs. 140-141)?

3. The Magnet and the Solenoid.

Experiment 6.

Make a helix, or coil, of wire two or three inches long by winding insulated copper wire No. 20 around a lead pencil. Connect the ends of the wire to the poles of a battery, and pass a magnetic needle around the coil.

1. How does the magnetic needle set itself when placed (1) near each end of the spiral, (2) midway between the ends?

2. In what particulars does the helix resemble a bar magnet?

3. What pole of the helix is the observer in front of when the current in the coils facing him is passing in the direction of the hands of a clock?

Experiment 7.

Make a helix of insulated wire, No. 16 or 18, about $\frac{3}{4}$ inch in diameter and three inches long, and place it in a rectangular opening made in a sheet of cardboard, so that its axis will be in the plane of the cardboard (Fig. 142). This can be done by cutting out the three sides of a rectangle of the proper size, and then passing the free end of the strip through the

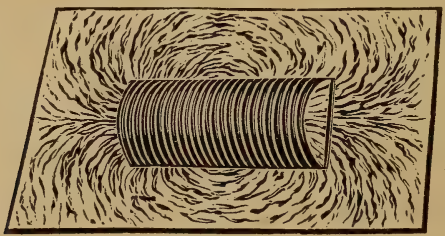

Fig. 142.

centre of the helix, and replacing the strip in position. Sprinkle iron filings from a muslin bag on the cardboard around the helix and within it. Attach the ends of the wire to the poles of a battery, and gently tap the cardboard.

How do you account for the way in which the iron filings arrange themselves?

The above experiments show that a **helix of wire through which an electric current is passing acts exactly like a magnet, having two poles and a neutral equatorial region.** The field which surrounds it resembles that of a bar magnet.

Such a coil is sometimes called a **solenoid.**

4. Electro-Magnets.

Experiment 8.

Repeat Experiment 4, passing a small soft iron rod through the helix before the current is passed through the wire.

1. What effect has the introduction of the iron upon the magnetic power of the helix?

2. Are the N-seeking and S-seeking poles at the same ends of the helix as before the insertion of the core?

Will the end of the rod lift up a small piece of iron, say a tack, (1) when the current is passing through the wire, (2) when the circuit is not completed?

A soft iron core surrounded by a helix of insulated wire, through which an electric current can be passed, is called an **electro-magnet.**

Why is an electro-magnet a more powerful magnet than a solenoid?

To answer this question repeat Experiment 6, placing a soft iron core in a helix of wire.

1. How does the arrangement of the iron filings on the card differ from that observed when the core was not inserted?

When the helix is used without the core the greater number of the lines of force pass in circles around the individual turns of wire, and but a few run through the helix from end to end, and back again outside the coil; but when the iron core is inserted the greater number of

the lines of force pass in this way, because the permeability of iron is very much greater than that of air, and whenever a coil passes near the core, the lines of force, instead of passing in closed curves around the wire, change their shape and pass from end to end of the core. The effect of the core, therefore, is to increase the number of lines of force which are concentrated at definite poles, and consequently to increase the power of the magnet.

5. Polarity of an Electro-Magnet and Direction of the Current.

Looking at the S-seeking pole of an electro-magnet, the magnetizing current is passing through the coils in the direction of the hands of a clock, and, looking at the N-seeking pole, the current is circulating in the opposite direction (Fig. 143).

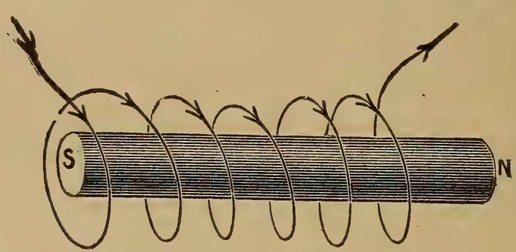

FIG. 143.

6. Use of Solenoid.

Experiment 9.

Make a solenoid about 4 inches long by winding four or five layers of No. 20 insulated wire around a glass or cardboard tube. Connect the ends of the wire with a battery, hold the tube in a vertical position, and take a short soft iron rod which will just slip easily into the bore of the tube, and insert it part way into the tube.

How does the rod tend to set itself within the helix?

A solenoid with a movable iron plunger is frequently used instead of an electro-magnet, with a permanent core, when the magnet is required to give a pull through a long range.

7. Laws of Magnets.

Experiment 10.

Take a soft iron rod $1\frac{1}{2}$ inches in diameter and two or three inches long, and wind around it one layer of insulated wire No. 20. Connect the ends of the wire with the poles of a battery, and test the lifting power of the magnet by trying to lift small pieces of iron with it. Repeat the experiment, winding two, three, four, etc., layers of wire on the rod.

1. What effect has increasing the number of layers of wire upon the power of the magnet? Why?

2. If the same difference in potential is always maintained between the ends of the wire, will the power of the magnet always continue to be affected in the same way by increasing the number of turns of wire? If not, why?

3. If the same current is maintained in the wire, will the power of the magnet always continue to be affected in the same way by increasing the number of turns of wire? Give reasons for your answer.

Experiment 11.

Connect in a circuit with a battery an electro-magnet and a rheostat, or series of resistance coils. Test the lifting power of the magnet. By lessening the number of the coils of the rheostat in the circuit, increase the current. Again test the lifting power of the magnet.

What effect has increasing the current on the lifting power of the magnet?

Repeat the experiment, decreasing the current by increasing the resistance.

1. What change now takes place in the strength of the magnet?

2. What is the relation between the current and the strength of the magnet? Why?

These experiments illustrate the following laws:

8. Laws of Magnets.

1. **The strength of an electro-magnet is proportional to the strength of the current.**

2. **The strength of an electro-magnet is proportional to the number of turns of wire, if the current is kept constant.**

These laws are true only when the iron core is not near the point of being magnetized to saturation.

It should also be observed that when an electro-magnet is used with a battery, or other source of current where the ends of the wire are kept at a constant difference in potential, an increase in the number of turns of the wire may not necessarily add to the strength of the magnet, because the loss in power through loss in current caused by increased resistance may more than counterbalance the gain through the increased number of turns of wire.

In what circuit should a "long coil" electro-magnet (one with a great number of turns of fine wire) be used, one in which the remaining resistance is great or small as compared with the resistance of the magnet?

9. Laws of Currents.

Experiment 12.

Wind insulated magnet wire, No. 20, into coils of the forms A and B in Fig. 144. A is about 25 cm. square and contains five convolutions of the wire. It may be made by winding the wire around the edge of a square board, tying the strands together at a number of points with thread, and removing the

board. B may be made in a similar manner. It is rectangular, 20 cm. x 10 cm., and contains also five convolutions.

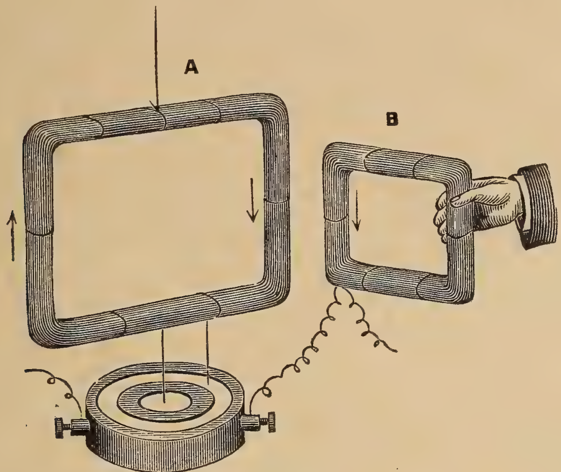

FIG. 144.

Suspend A by a long thread and allow the ends of the wire to dip into the mercury receptacles as in Experiment 5, page 187. Connect the wires as shown in Fig. 144, so that a current from a battery of three or four cells will pass by one continuous circuit through the two coils.

Bring one edge of B near one of the vertical edges of A with the planes of the coils at right angles to each other in

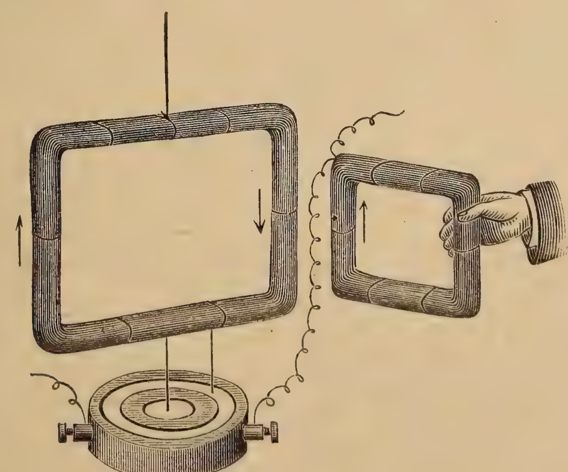

FIG. 145.

such a position that the current in the adjacent portions of the two coils will flow

(1) In the same direction (Fig. 144);

(2) In opposite directions (Fig. 145).

What happens in each case?

Hold B within A as shown in Fig. 146, arranging the connecting wires in such a way that A is free to turn around.

How does the coil A tend to get itself relatively to B?

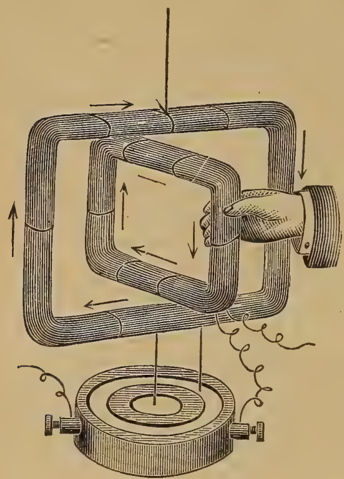

FIG. 146.

The above Experiments illustrate the following laws of currents:—

1. **Parallel currents in the same directions attract each other; parallel currents in opposite directions repel each other.**

2. **Angular currents tend to become parallel and to flow in the same direction.**

When the currents flow in the same direction, their magnetic fields tend to merge, and the stress in the medium which surrounds the wires tends to draw them together, but when the currents flow in opposite directions the stresses tend to push the wires further apart.

Show how the second law results from the doctrine of stresses in the medium surrounding the wires.

To show the directions of the lines of force in the fields repeat Experiment 3, page 186, passing two wires through the card and causing the current to pass (1) in

the same direction through each wire (Fig. 147), (2) in opposite directions (Fig. 148).

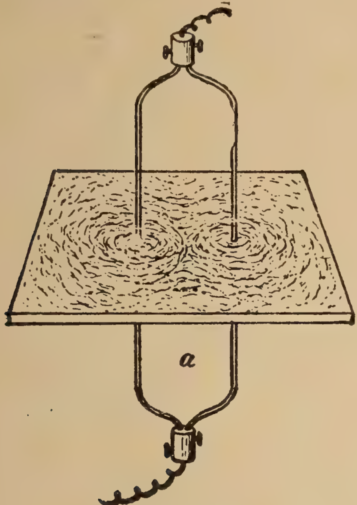

FIG. 147.

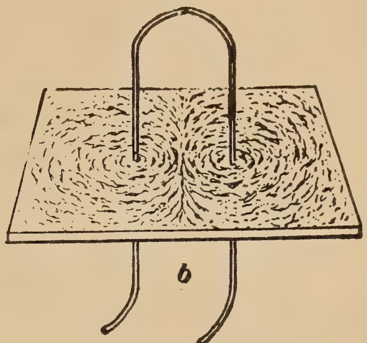

FIG. 148.

II—Practical Applications of the Magnetic Effects of the Current.

1. The Electric Telegraph.

The telegraph instruments are the **key**, the **sounder** and the **relay**.

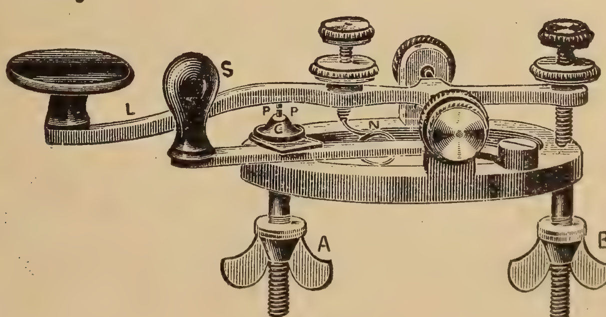

FIG. 149.

The Key.

The key is an instrument for closing and breaking the circuit. Fig. 149 shows its construction. Two platinum

contact posts P, P, are connected with the binding posts A and B, the lower one being connected by a bolt C insulated from the frame, and the upper being mounted on the lever L which is connected with the binding post B by means of the frame. The key is placed in the circuit by connecting the ends of the wire to the binding posts.

When the lever is pressed down the platinum points are brought into contact and the circuit is completed. When the lever is not depressed a spring N, keeps the points apart. A switch S, is used to connect the binding posts, and close the circuit when the instrument is not in use.

The Sounder.

Fig. 150 shows the construction of the sounder. It consists of an electro-magnet E, above the poles of which is a soft iron armature A, mounted on a pivoted beam B, the beam being raised and the armature held by a

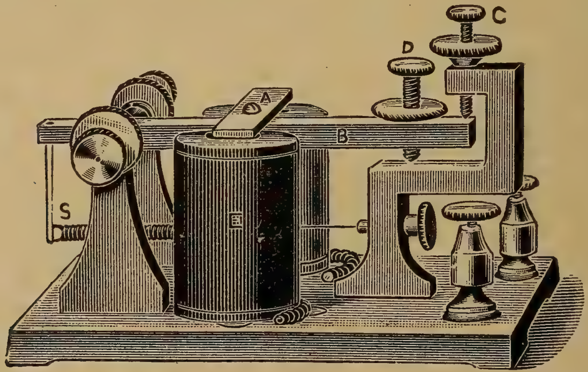

FIG. 150.

spring S, above the poles of the magnet at a distance regulated by the screws C and D. The ends of the wire of the magnet are connected with the binding posts.

The Relay.

The relay is an instrument for closing automatically a local circuit in an office when the current in the main circuit, on account of the great resistance in the line, is too weak to work the sounder. It is a key worked by an electro-magnet instead of by hand. Fig. 151 shows its construction. It consists of a "long coil" electro-

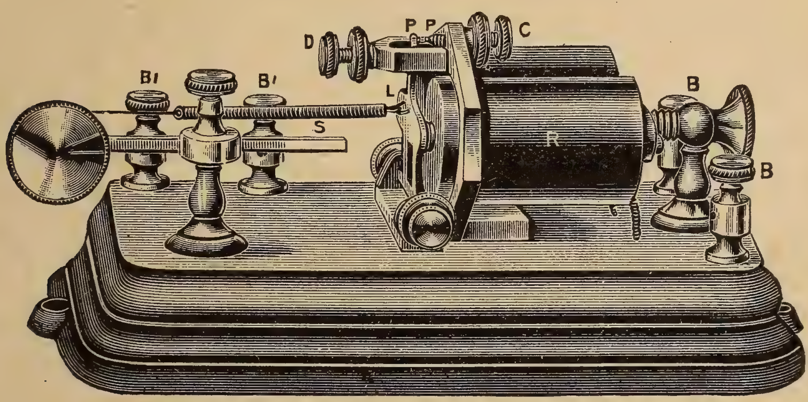

FIG. 151.

magnet R, in front of the poles of which is a pivoted lever L carrying a soft iron armature, which is held a little distance from the poles by a spring S. Platinum contact points P, P, are connected with the lever L and the screw C. The ends of the wire of the electro-magnet are connected with binding posts B, B, and the lever L and screw C are electrically connected with the binding posts B_1, B_1.

Whenever the magnet R is magnetized the armature is drawn toward the poles and the contact points P, P, are brought together and the local circuit completed.

Why should the magnet in this instrument be a "long coil" magnet?

Fig. 152 shows a telegraph line passing through three offices, A, B and C, and indicates how the connections are made in each office.

Action.

When the line is not in use the switch on each key is closed, and the current in the main circuit flows from the copper plate connected with the wire at the main battery at A through the wire, across the switches of the keys, and through the electro-magnets of the relays, to the first zinc plate of the main battery at C, and from the zinc plates to the copper plates through the fluid of the battery, and thence through the wire to the ground, which forms the return circuit to the zinc plate of the main battery at A. The magnets R, R, R are magnetized, the local circuits completed by the relays, and the current from each local battery flows through the magnet E of the sounder, thus holding the screw D against the frame.

When the line is to be used by an operator in any office A, the switch of the key is opened, the circuit broken, and the armature of the relay and of the sounder in each of the offices released.

When he depresses the key and completes the main circuit, the armature of the relay in each office is drawn in, the local circuit is completed, and the screw D of each sounder is drawn down against the frame, producing a click. When he breaks the circuit at the key, the armature of the relay in each office is released, the local circuit is broken, and the beam of each sounder is drawn up by the spring against the screw C, producing another click. When the circuit is completed and broken quickly by the

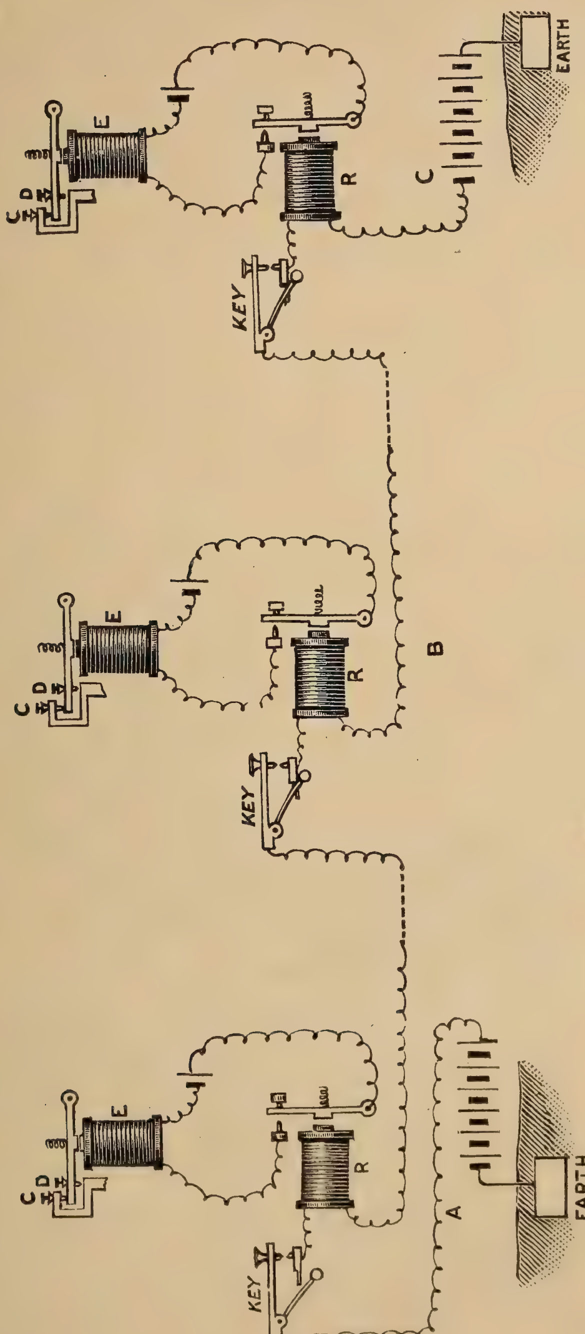

FIG. 152.

operator, the two clicks are very close together, and a "dot" is formed; but when an interval intervenes between the clicks the effect is called a "dash." Different combinations of "dots" and "dashes" form different letters. The operator is thus able to make himself understood by the listener.

The following is the code of signals generally adopted in America:

MORSE CODE OF SIGNALS.

A · —	H · · · ·	O · ·	V · · · —
B — · · ·	I · ·	P · · · · ·	W · — —
C · · ·	J — · — ·	Q · · — ·	X · — · ·
D — · ·	K — · —	R · · ·	Y · · · ·
E ·	L ——	S · · ·	Z · · · ·
F · — ·	M — —	T —	& · · · ·
G — — ·	N — ·	U · · —	

NUMERALS.

1 · — — ·	3 · · · — ·	5 — — —	7 — — · ·	9 — · · —
2 · · — — · ·	4 · · · · —	6 · · · · · ·	8 — · · · ·	0 ———

PUNCTUATION.

Period · · — — · ·	Interrogation — · · — ·	Paragraph — — — —
Comma · — · —	Exclamation — — — ·	Italics — · · · —
Semicolon · — · — ·	Parenthesis · — · · —	

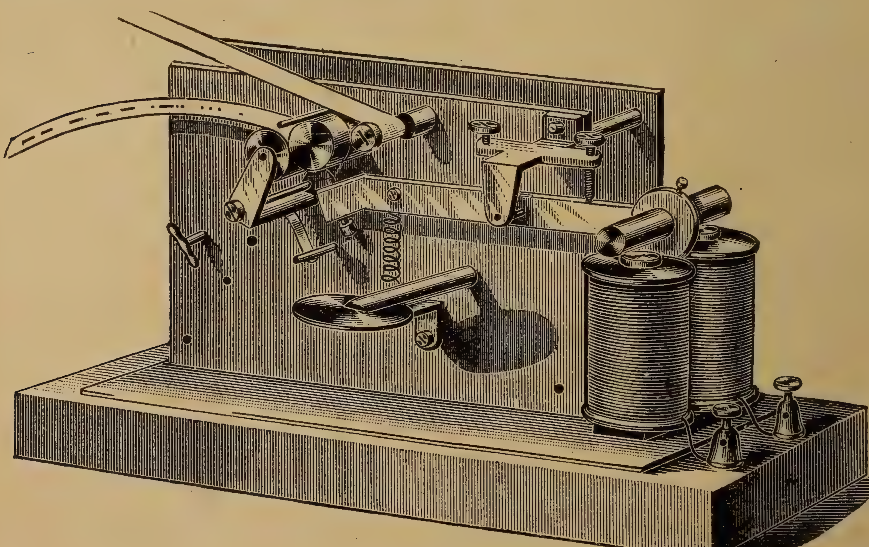

FIG. 153.

Instead of taking by sound it was formerly customary to read the dots and dashes on a paper strip, as they were made by a point attached to the beam bearing the armature, while the strip was kept moving by clock-work. Fig. 153 shows the instrument which was used, in the place of a sounder, for this purpose.

2. Electric Bells.

Construction.

Electric bells are of various kinds. Fig. 154 shows the construction of one of the most common forms. It consists of an electro-magnet E, in front of the poles

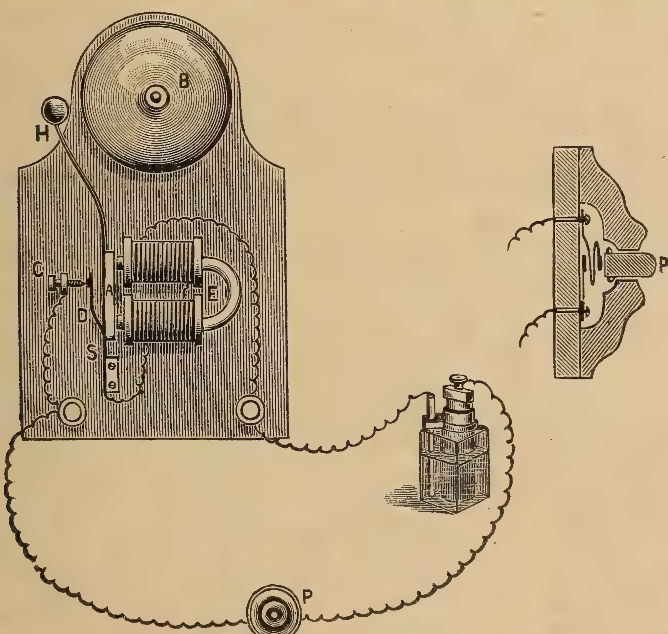

FIG. 154.

of which is supported an armature A by a spring S. At the end of the armature is attached a hammer H, placed in such a position that it will strike a bell B when the armature is drawn in to the poles of the magnet. A current breaker, consisting of a platinum-tipped screw C

in contact with a platinum-tipped spring D attached to the armature, is placed in the circuit as shown in the figure.

Action.

When the circuit is completed by a push button P, the current from the battery passes from the screw C to spring D, through the electro-magnet and back to the battery. The armature is drawn in and the bell struck by the hammer; but by the movement of the armature the spring D is separated from the screw C, and the circuit is broken at this point. The magnet then releases the armature, the spring S causes the hammer to fall back into its original position, the circuit is again completed, and the action goes on as before. A continuous ringing is thus kept up.

3. Measurement of Current Strength—Galvanometers.

Since the magnetic effect of the current varies with its strength, the strengths of different currents may be compared by comparing their magnetic actions. Instruments

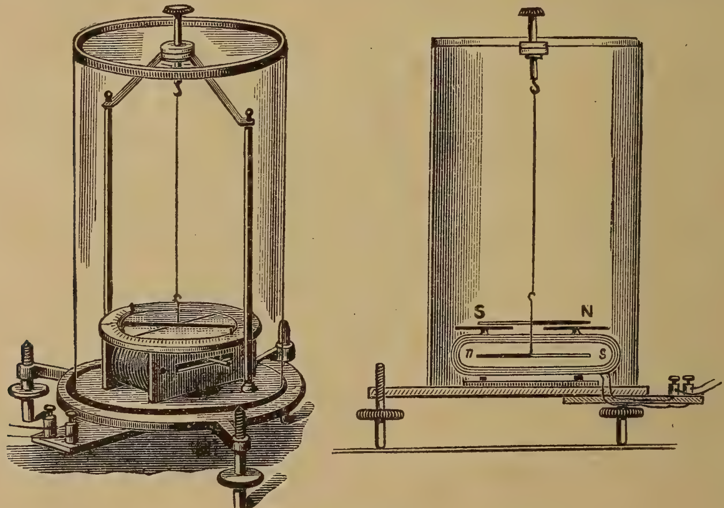

FIG. 155.

for this purpose are called **galvanometers.** There are many forms of these instruments, but the following are among the most common.

10. The Astatic Galvanometer.

Construction.

Fig. 155 shows the construction of this instrument. It consists of an astatic pair of magnetic needles, that is, a pair of magnetic needles rigidly connected as shown in Fig. 114, suspended by a silk fibre in such a position that one of the needles, usually the lower one, is free to turn around within a coil of wire, the ends of which are attached to the binding posts of the instrument. The deflection is read from a circular graduated scale placed above the coil.

Action.

When the needles are parallel with the strands of the coil, and a current passed through it, both needles will be urged in the same direction. If the deflection of the needle is not more than 15° or 20°, the strength of the current will be approximately proportional to the angle of deflection.

This instrument is much more sensitive than the galvanoscope described on page 296, Part I.; because (1) the needles are independent of the directive influence of the earth's magnetism and consequently are more readily turned in the magnetic field produced by the current, (2) the current acts upon both needles and tends to turn them in the same direction.

The number of turns of wire in the coil will depend on the character of the current to be measured.

It is made sensitive to weak currents :—

(1) By winding the coil with a large number of turns of wire.

(2) By suspending the needle by a fibre of which the torsion is very low.

(3) By magnetizing the needles strongly.

Apply the law stated on page 186 to explain why the current in the coil tends to turn both needles of the astatic pair in the same direction.

11. The D'Arsonval Galvanometer.

In the D'Arsonval galvanometer, the permanent magnet remains stationary, and a suspended coil revolves through the action of the current in the field of the permanent magnet. Fig. 156 shows the essential parts of the instrument. N and S are the poles of a permanent magnet of the horse-shoe type. C is an elongated coil suspended between wires A and B, which lead the current to and from the coil. D is a mirror attached to the upper part of the coil for reflecting a beam of light, which serves as a pointer to indicate the extent of the rotation of the coil.

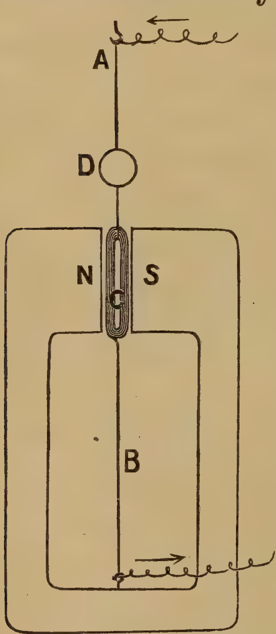

Fig. 156.

12. The Tangent Galvanometer.

Construction.

Fig. 157 shows the construction of a tangent galvanometer. It consists of a short magnetic needle, not exceeding one inch in length, suspended, or poised, at the

centre of an open ring of copper or circular coil of copper wire not less than 12 inches in diameter. Where a large

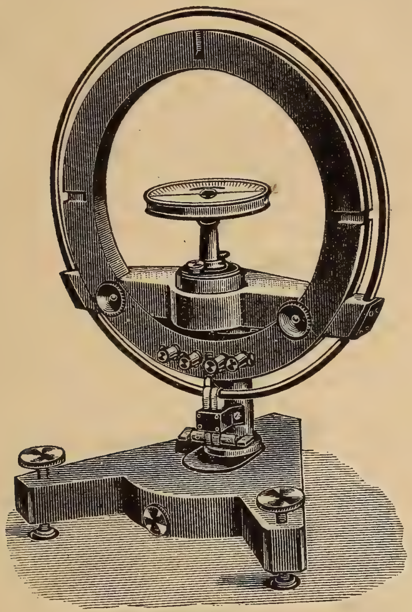

FIG. 157.

range of currents is to be measured, both the open ring and coils of different numbers of turns of wire are sometimes mounted on the same instrument as shown in the figure. A light aluminium pointer is attached to the needle, and its deflection is read on a circular graduated scale placed under the pointer.

Action.

Since the coil is large and the needle short, the magnetic field which a current passing through the ring produces is practically uniform at all points immediately surrounding the needle, and the lines of force there are at right angles to the plane of the coil (Fig. 148). On these conditions, when the coil is placed parallel with the earth's magnetic meridian and a current passed through

it, **the intensity of the current will vary as the tangent of the angle of deflection of the needle.** This may be demonstrated as follows:—

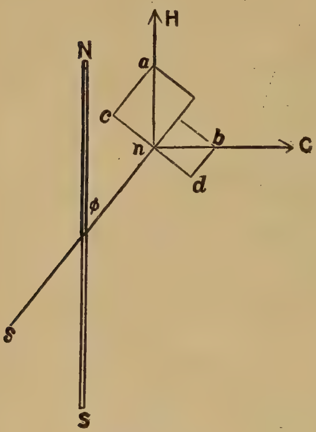

Fig. 158.

Let NS represent the coil of the galvanometer (Fig. 158);

and let ns denote the direction of the needle and ϕ the angle of deflection when a current C passes through the coil.

Two forces act upon the needle.

(i) The horizontal component of the earth's magnetism (H), acting in the direction of the magnetic meridian.

(ii) The force due to the magnetic effect of the current acting at right angles to (i). It is proportional to the intensity of the current, and may, therefore, be represented by C.

Let the lines na and nb represent these forces in magnitude and in direction.

If the forces are resolved along two lines, one in the direction of the needle and the other at right angles to it, only the resolved parts in a direction at right angles to the needle tend to turn it around.

These resolved parts are represented by the lines nc and nd, and, since the needle is at rest

$$nc = nd,$$

but $$nc = na \sin nac$$
$$= na \sin \phi$$

and $$nd = nb \cos bnd$$
$$= nb \cos \phi$$

therefore $$na \sin \phi = nb \cos \phi,$$

or $$\frac{nb}{na} = \frac{\sin \phi}{\cos \phi} = \tan \phi$$

or $$nb = na \tan \phi.$$

But nb represents C, and na represents H,

therefore $$C = H \tan \phi,$$

but H is constant.

Hence

$$C \text{ varies as } \tan \phi.$$

That is, **the intensity of the current varies as the tangent of the angle of deflection of the needle.**

If the current corresponding to any angle of deflection is known, the current corresponding to any other angle of deflection can be determined by referring to a table for the tangent of the angle, and making the necessary calculations.

Experiment 1.

Place in a circuit with a constant battery a tangent galvanometer and a copper voltameter, observe the reading of the galvanometer, and determine, as described in Art. 11, page 181, the current in amperes passing through the coil of the galvanometer.

Make a record of the result and keep it for future experiments.

QUESTIONS.

1. If you were given a voltaic cell, wire with an insulating covering, and a bar of soft iron, one end of which was marked, state exactly what arrangements you would make in order to magnetize the iron so that the marked end might be a north-seeking pole. Give a diagram.

2. A current is flowing through a rigid copper rod. How would you place a small piece of iron wire with respect to it, so that the iron may be magnetized in the direction of its length? Assuming the direction of the current, state which end of the iron will be a north pole.

3. A strong electric current flows through a copper wire, which passes through the centre of an iron ring, and is at right angles to the plane of the ring. Describe the magnetic state of the ring.

4. A telegraph wire runs north and south along the magnetic meridian. A magnetic needle free to turn in all directions is placed beside the wire, and on the same level with it. How will this needle act when a current is sent through the wire from south to north? Supposing the wire to run east and west, how would you detect the direction of a current passing through it?

5. A gutta-percha covered copper wire is wound round a wooden cylinder, AB, from A to B. How would you wind it back from B to A, (1) so as to increase, (2) so as to diminish the magnetic effects which it produces when a current is passed through it? Illustrate your answer by a diagram drawn on the assumption that you are looking at the end B.

6. An insulated copper wire is wound round a glass tube, AB, from end to end, and a current is sent through it, which to an observer looking at the end A, appears to go round in the same direction as the hands of a watch. A rod of soft iron is held (1) inside the tube; (2) outside but parallel to the tube. What will be the magnetic pole at that end of the bar which is nearest to the observer in each case?

7. Two parallel covered wires are traversed by equal currents in the same direction: what is the joint effect of the currents upon a bar of soft iron (*a*) laid across the two wires, on the same side of both; (*b*) held between the wires at the same distance from each?

8. Two compass needles are arranged near each other so that both point along the same straight line. A wire connecting the platinum and zinc ends of a battery is stretched vertically half-way between the needles. How will the current in the wire affect the needles, and how will the result depend upon whether the platinum terminal is connected with the upper or the lower end of the wire?

9. Two long wires are placed parallel to each other in the same horizontal plane, and in the magnetic meridian. A magnetic needle, capable of turning in any direction about its point of suspension is placed exactly half-way between them. How will it

behave, if the same electric current flows through the easterly wire from south to north, and through the westerly wire from north to south? (The action of the earth on the magnetic needle may be neglected.)

10. One end of a coil of wire, through which a current passes, is found to attract the north pole of a compass-needle, when placed at a certain distance from it. Will the action be the same (1) in nature, (2) in amount, when a rod of soft unmagnetized iron is placed inside the coil?

11. A number of galvanic cells are connected together in a row to form a battery. This row is laid on a table so as to lie north and south. The zinc is to the north. The poles of the battery are connected together by a wire, which passes from one pole, up one wall of the room, across the ceiling, and down the opposite wall to the other pole of the battery. How will a magnetic needle be affected which is placed under the table and just below the battery?

12. A coil of wire is suspended in front of the one pole of a bar magnet. A current is made to flow in the coil. How will the coil move (1) when its axis points in the line of the magnet, (2) when it points at right angles to that line?

13. A small coil is suspended between the poles of the powerful electro-magnet and is movable about a vertical axis. How will it move when a current flows in it? If set in a certain position it will not move. What is this position?

14. If it were true that the earth's magnetism is due to currents traversing the earth's surface, show what would be their general direction.

15. An elastic spiral of wire hangs so that its lower end just dips into a vessel of mercury. Describe and explain what happens when the top of the spiral is connected with the one pole and the mercury is connected with the other pole of a battery.

CHAPTER XV.

CURRENT INDUCTION.

I.—Induced Currents.

1. Apparatus.

Prepare two large coils of the form shown in Fig. 159, by winding double cotton-covered magnet wire No. 16 on wooden spools of which the dimensions are, length 4 inches, diameter of flanges 3 inches, diameter of the opening through the spool

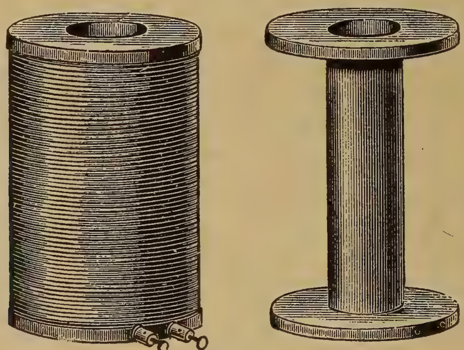

FIG. 159.

1 inch, thickness of walls $\frac{1}{16}$ inch, thickness of flanges $\frac{1}{2}$ inch. The wire should be carefully wound on each in the same direction, and the ends attached to binding posts, as shown in the figure.

FIG. 160.

Also prepare another coil (Fig. 160), made by winding magnet wire No. 35 on a spool of the following dimensions: length 4 inches, diameter of flanges $\frac{15}{16}$ inch, diameter of opening through the spool $\frac{7}{16}$ inch, with the thickness of walls and flanges as in the large spools.

Obtain two soft iron rods, one 10 inches long, which will just pass easily through the opening in the large spool, and another 5 inches long, which will just pass

through the opening in the small spool. Also obtain two soft iron rods $4\frac{1}{4}$ inches long and 1 inch in diameter, to be connected as shown in Fig. 161 by an iron plate, 6 inches long and $\frac{1}{2}$ inch thick, the centres of the rods being $4\frac{1}{2}$ inches apart, and their upper ends being bored and tapped to receive bolts. The plate should be secured to a wooden stand, and when the large coils are fitted over the rods the apparatus should appear as shown in Fig. 164.

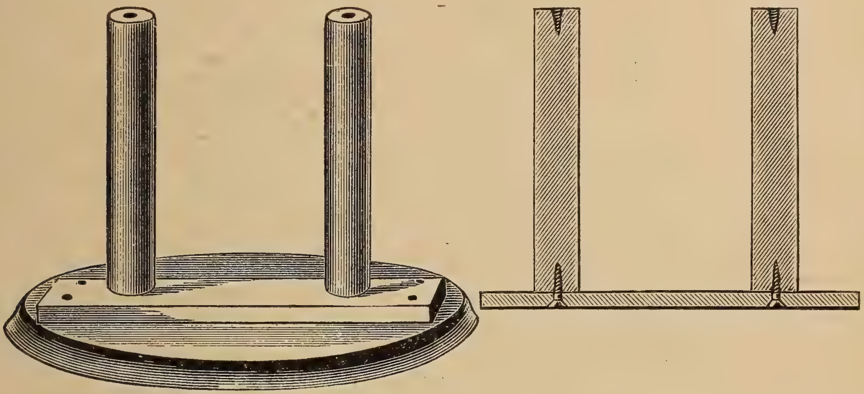

Fig. 161.

2. Production of Induced Currents.

Experiment 1.

Connect the ends of the wire of one of the large coils with a sensitive galvanometer, and thrust (1) slowly, (2) quickly, a powerful bar magnet into the opening of the spool (Fig. 162).

1. Does the galvanometer indicate a current (1) at the instant the magnet is thrust into the coil, (2) while it remains stationary in the coil?

Withdraw the magnet (1) quickly, (2) slowly.

2. Does the galvanometer indicate a current at the instant the magnet is withdrawn?

3. If a current is produced by (*a*) inserting, and (*b*) withdrawing the magnet from the coil, does it flow in the same direction in each

case, and is there any relation between the E.M.F. of these currents and the rapidity with which the magnet is inserted or withdrawn?

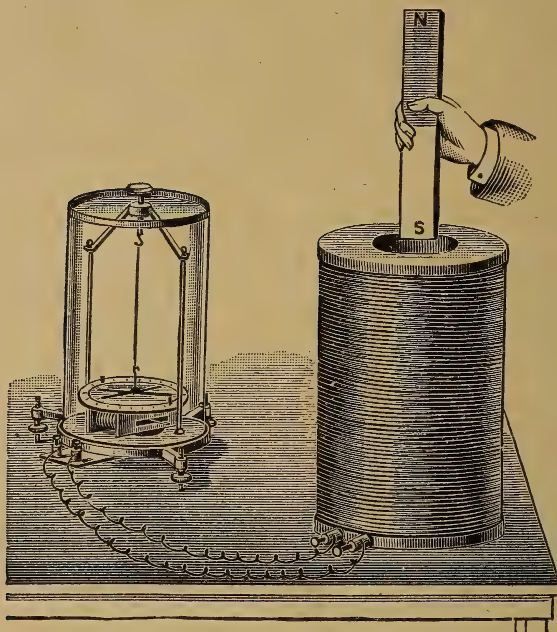

FIG. 162.

4. Does the inserting of the magnet increase or diminish the number of magnetic lines of force which pass across the space enclosed by the coil? What effect has withdrawing it upon the number of lines of force passing across the space?

Experiment 2.

Make an electro-magnet by placing the soft iron rod within the small coil of fine wire prepared as described above and connecting the ends of the wire with a battery. Place the galvanometer in the circuit for an instant and observe the direction of the deflection of the needle. Now remove the galvanometer from this circuit and connect it with the large coil, as shown in Fig. 163, taking care to connect each binding post with the end of the wire of the large coil which corresponds to the end of the small coil with which it was connected.

When the small coil is connected with the battery, thrust it quickly into the large coil, allow it to stand a few seconds and then withdraw it quickly. Repeat the experiment several times, changing the rapidity with which the coil is inserted and withdrawn.

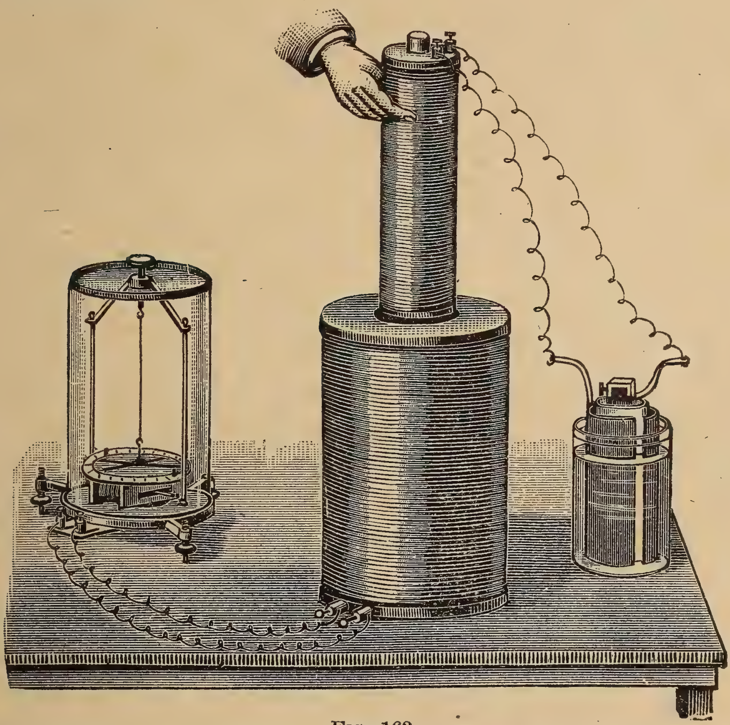

FIG. 163.

1. When does the galvanometer indicate that a current is flowing through the coil connected with it?

2. When does this current flow in the same direction as the battery current, when the coils are approaching or when they are receding from each other?

3. What is the relation between the rapidity with which the coils are brought together, or separated, and the E M.F. of the current produced in the coil connected with the galvanometer?

3. Explanation of Terms.

The coil connected with the battery is called the **primary coil**, and the current which flows through it is

called the **primary current**; the coil connected with the galvanometer is called the **secondary coil**, and the momentary currents made to flow in it, **secondary currents.** When the secondary currents flow in the same direction as the primary, they are said to be "**direct**," or to flow in a **positive direction**; but when the secondary currents flow in the opposite direction, they are said to be "**inverse**," or to flow in a **negative direction.**

Is the secondary current direct or inverse when the number of lines of force passing through the space enclosed by the secondary coil is (1) increasing, (2) decreasing?

4. Laws of Induction.

Experiments 1 and 2 show:—

1. **Whenever a decrease in the number of lines of force which pass through a closed circuit takes place, a current is induced in this circuit flowing in the same direction as that which would be required to produce this magnetic field, that is, a direct current is produced.**

Whenever an increase in the number of lines of force takes place, the current induced is such as would by itself produce a field opposite in direction to that acting; that is, an inverse current is produced.

2. **The total electromotive-force induced in any circuit at a given instant is equal to the time-rate of the variation of the flow of magnetic lines of force across this circuit.**

5. Lenz's Law.

We have found (*a*) that parallel currents in the same direction attract each other (Art. 9, page 194), (*b*) that on moving a current from a conducting circuit, an induced current is produced in the secondary in the same direction as in the primary (Experiment 2, page 212). We have also found (*a*) that parallel currents in opposite directions repel each other, and (*b*) that on moving a

current towards a conducting circuit an induced current is produced in the secondary in the opposite direction to that in the primary.

Hence in all cases of electro-magnetic induction, **the direction of the induced current is always such that it produces a magnetic field opposing the motion or change which induces the current.** This is known as **Lenz's Law.**

6. Experiments Illustrative of the Laws of Induction.

Perform the following experiments, noting in each case:—

(*a*) The cause of the induced current produced.

(*b*) The conditions on which (*a*) a direct current, (*b*) an inverse current, is produced.

(*c*) Whether your observations conform to Lenz's Law.

1. Repeat Experiment 2 above, connecting the battery with the outer coil and the galvanometer with the inner coil.

2. Place the two large coils on the vertical rods shown in Fig. 161, and connect them as shown in Fig. 164, thus forming

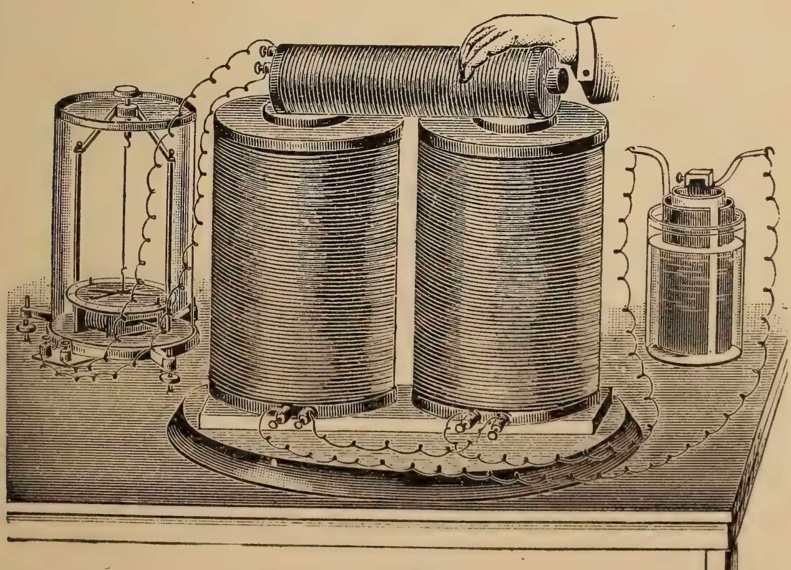

Fig. 164.

a large electro-magnet with opposite poles at the upper ends of the rods. Connect with the battery as shown in the figure. Place the iron rod within the small coil and connect the terminals with the galvanometer. Hold this coil over the poles of the electro-magnet, and keeping its axis in line with the poles of the magnet, move it backward and forward and turn it end for end.

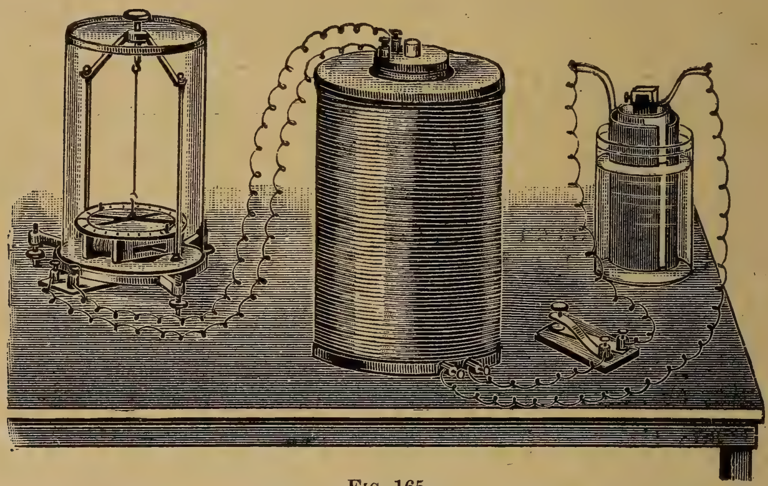

FIG. 165.

3. Place the small coil within the large one, insert the iron rod, and connect the small coil with the galvanometer and the large one with a battery, placing a key in the latter circuit, as shown in Fig. 165. Quickly make and break the circuit two or three times with the key.

4. Repeat the last Experiment, connecting the outer coil with the galvanometer and the inner one with the battery.

5. Repeat Experiments 3 and 4, placing in the circuit a rheostat instead of the key.

Alternately lessen and increase the current given by the battery by increasing and decreasing with the rheostat the resistance in the circuit.

6. Repeat Experiments 3, 4, and 5, using the two large coils instead of the large one and small one, and (1) placing them

end to end, as shown in Fig. 166, with an iron rod through the openings, (2) placing them on the upright rods, as shown in Fig. 167.

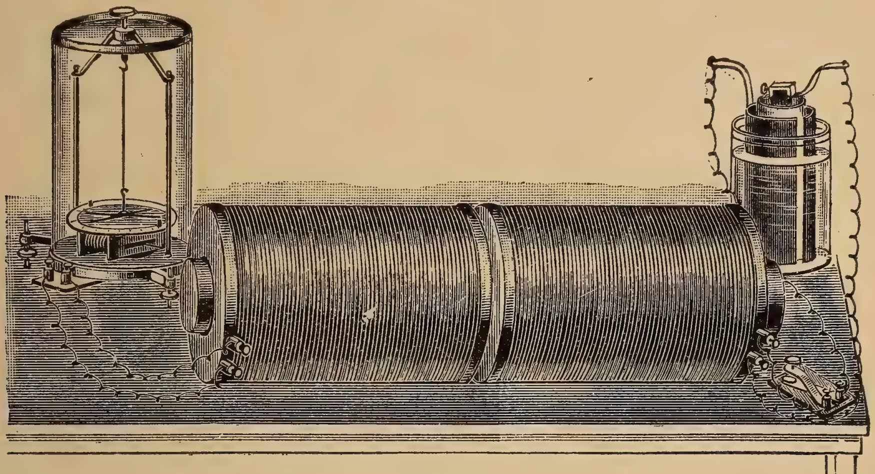

Fig. 166.

7. Place the coils again as in Experiment 3. Connect the outer one with the battery and the inner one with the galvanometer, and move backward and forward in front of the iron rod a plate of soft iron.

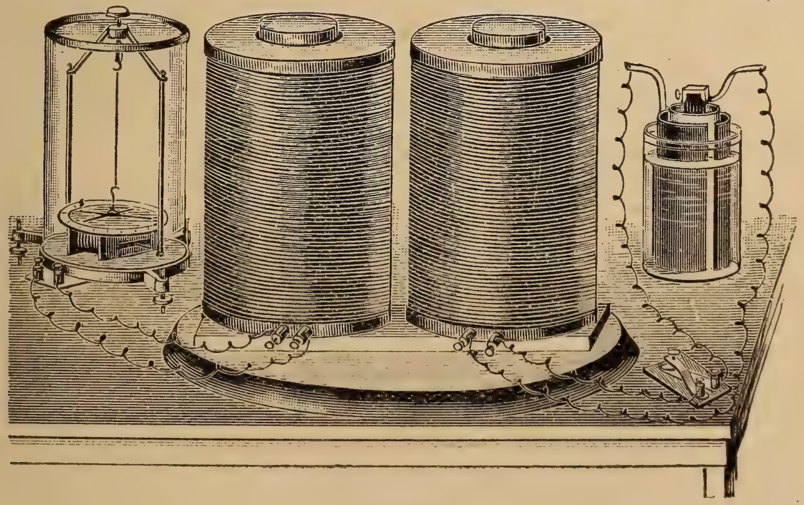

Fig. 167.

7. Self-Induction.

Experiment 3.

Place the large coils arranged as an electro-magnet, as shown in Fig. 164, in a circuit with a battery. Close and open the circuit by holding the ends of the wires in your hands, touching them together, and then separating them.

1. What do you observe at the ends of the wires when they are separated?

2. Is a shock felt? Dampen your fingers and repeat the experiment, grasping the bare wires.

The effects observed are due to what is known as **self-induction.**

The magnetic lines of force surrounding a current in circulating around the wire pass, especially when the wire is coiled, across contiguous parts of the same circuit, and any variation in the strength of the current causes the current to act inductively on itself. On completing the circuit, this current is inverse; and on breaking it, direct.

The direct induced current in the primary wire itself, which tends to strengthen the current when the circuit is broken, is called the **extra current.**

This self-induced current is of high E.M.F., and therefore flows for an instant across the air space when the wires are a short distance apart; hence the spark.

1. Why will an iron core placed within a coil of wire in a circuit increase the intensity of the extra current when the circuit is broken?

2. If a large electro-magnet is placed in a circuit with a galvanometer and a secondary battery, on closing the circuit the current

will be seen to rise gradually and take its full strength only after several seconds. Explain.

3. If when you place across the terminals of a large electro-magnet an incandescent lamp of such resistance that a battery current will bring it only to dull redness, you break the connection with the battery, you will observe that the lamp will become vividly incandescent for an instant Explain. Try the experiment.

QUESTIONS.

1. You have a metal hoop. Describe (and give a figure of) some arrangement by which, without touching the hoop, you could make electric currents pass around it, first one way and then the other.

2. A bar of perfectly soft iron is thrust into the interior of a coil of wire whose terminals are connected through a galvanometer. An induced current is observed. Could the coil and bar be placed in such a position that the above action might nearly or entirely disappear? Explain fully.

3. A piece of covered wire is passed a few times round a wooden hoop; its ends are joined up to a galvanometer. The ends of another piece of covered wire which is wrapped around a similar hoop are joined up to a battery. What will happen (1) if the two hoops are brought quickly near to each other, and (2) if they are quickly separated?

4. How could you temporarily stop or weaken a current in a wire without disconnecting it from the battery, by means of the motion of another wire through which a current is passing?

5. The poles of a voltaic battery are connected with two mercury-cups. These cups are connected successively by :—

(1) A long straight wire;

(2) The same wire arranged in a close spiral, the wire being covered with some insulating material;

(3) The same wire coiled round a soft iron core.

Describe and discuss what happens in each case when the circuit is broken.

6. Around the outside of a deep cylindrical jar are coiled two separate pieces of fine silk-covered wire, each consisting of many turns. The ends of one coil are fastened to a battery, those of the other to a sensitive galvanometer. When an iron bar is thrust into the jar a momentary current is observed in the galvanometer coils, and when it is drawn out another momentary current (but in an opposite direction) is observed. Explain these observations.

7. A small battery was joined in circuit with a coil of fine wire and a galvanometer, in which the current was found to produce a steady but small deflection. An unmagnetized iron bar was now plunged into the hollow of the coil and then withdrawn. The galvanometer needle was observed to recede momentarily from its first position, then to return and to swing beyond it with a wider arc than before, and finally to settle down to its original deflection. Explain these actions, and state what was the source of the energy that moved the needle.

II.—Practical Applications.

1.—Ruhmkorff Induction Coil.

The Ruhmkorff induction coil is an instrument by means of which currents of high E.M.F. are produced by

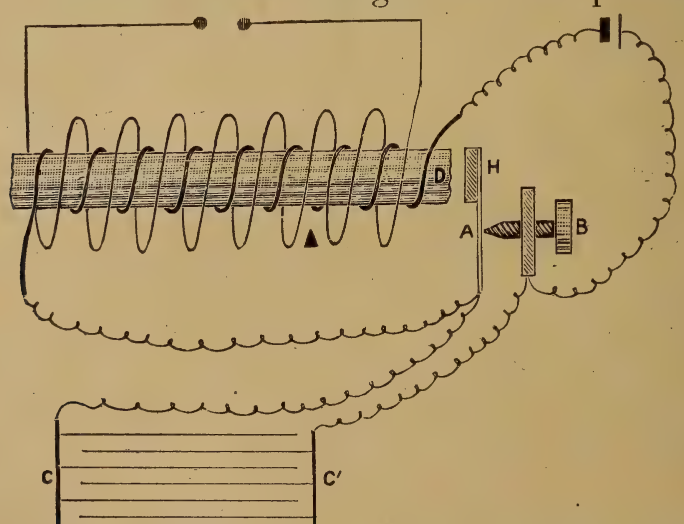

Fig. 168.

the action of an electric current in a circuit which is alternately opened and closed in rapid succession.

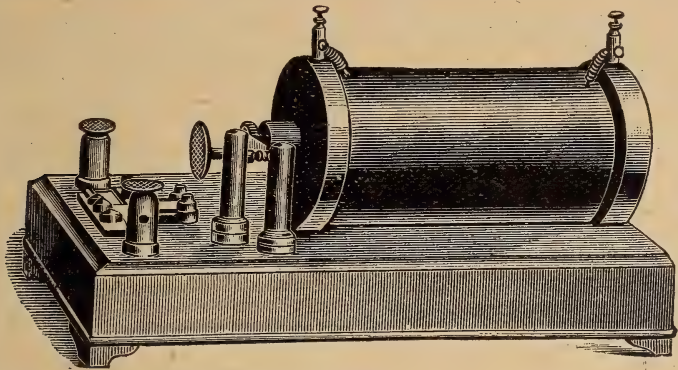

FIG. 168.

Construction.

Fig. 168 shows the essential parts of the instrument. A primary coil, consisting of a few turns of stout insulated copper wire, is wound around a core D made up of a bundle of soft iron wires. One end of this coil is attached directly to one of the poles of a battery; and the other end is connected to the other pole of the battery by means of a current breaker, which consists of a hammer H supported in front of the iron core by a spring A in contact with a screw B, the wires being connected as shown in the figure. The spring and screw are also connected with a condenser C, C^1 made of alternate layers of tinfoil and paraffined paper, in such a manner that one is joined to the even sheets of foil and the other to the odd ones.

A secondary coil, consisting of a great number of turns of very fine insulated wire, is wound on the outside of the primary coil. The terminals of this coil are attached to binding posts placed above the coil.

Action.

When the primary circuit is completed and the battery current passes through the coil, the core is magnetized, the hammer is drawn in, and the circuit broken between

the spring A and the screw B. The hammer then falls back, the circuit is completed, and the action goes on as before. An interrupted current is thus sent through the primary coil, which induces currents of high electromotive-force in the secondary coil.

The function of the condenser is to prevent the extra current induced in the primary coil, when the circuit is broken, from passing across the break in the form of a spark, and prolonging the time of fall to zero of the primary current, in consequence of which the rate of variation of the flow of the magnetic lines of force across the secondary coil would be diminished and the electromotive-force of the induced current lowered. The extra current flows by the shunt circuit into the condenser, and causes a difference in potential between the layers of foil connected with the two wires. This immediately gives rise to a current in the opposite direction which flows back through the primary coil and instantaneously demagnetizes the soft iron core, thus causing the direct current induced in the secondary coil, when the primary circuit is broken, to become shorter and more intense.

The potential-difference between the terminals of the secondary coil can in this way be made sufficiently great to cause a spark to pass between them when they are placed a short distance apart.

This potential-difference is increased by increasing the number of turns of wire, by increasing the current in the primary coil, and by decreasing the time required for it to fall to zero each time the circuit is broken.

The iron core, on account of its magnetic permeability, increases the number of lines of force passing through the coils.

A bundle of iron wire is used instead of a solid bar of iron to produce a stronger magnetization, and to prevent the circulation of induced currents in the iron itself.

2.—Applications of the Induction Coil.*

8. Electrical Discharges in Partial Vacua.

Experiment 1.

Connect the terminals of an induction coil with metal electrodes inserted into a glass vessel of the form shown in Fig. 169. Adjust the sliding electrode so that an electrical discharge will pass between the knobs, and exhaust the air from the vessel.

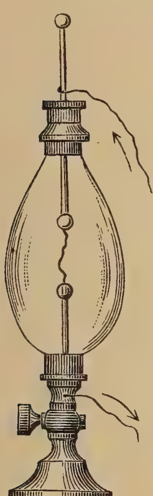

Fig. 169.

Observe the changes in the character of the discharge as exhaustion proceeds.

The effects of the electrical discharge in partial vacua are exhibited best in **Geissler Tubes.** These tubes are made in a great variety of forms (Fig. 170), and contain various rarefied gases usually at a pressure of about 2 mm. of mercury. The wires from the terminals of the induction coil are connected with platinum electrodes fused into the ends of the tubes. The colour effects of the tube depend mainly on the nature of the residual gas. Every gas glows with a more or less brilliant colour of its own. Fluorescent substances, such as uranium, glass or a solution of quinine, become beautifully luminous when placed within an excited tube.

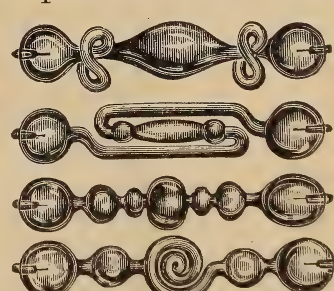

Fig. 170.

*If an induction coil of sufficient power is not available, a Toepler-Holtz or Wimshurst electric machine may be used in performing the experiments in this section.

The discharge within the Geissler tube is usually **stratified,** consisting of flickering layers of light separated by dark spaces.

Experiment 2.

Connect a Geissler tube with an induction coil and observe the beautiful play of light within the tube.

9. Discharges in High Vacua.

When the exhaustion of a vacuum tube is carried to a high degree, the dark space, which is observed to surround the cathode in a Geissler tube, expands until it fills the tube. The walls of the tube then show a brilliant fluorescence.

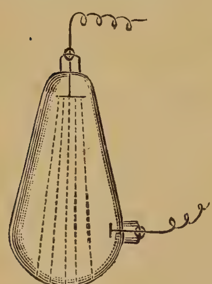

Fig. 171.

Tubes of this class are now usually known as **Crookes' tubes,** in honour of Sir William Crookes, who was one of the first to make an exhaustive study of the phenomena of electric discharges in high vacua. Fig. 171 shows one of the common forms used by him.

10. Cathode Rays—Their origin and properties.

An object placed in front of the cathode in a Crookes' tube (Fig. 172) casts a sharp shadow upon the walls of

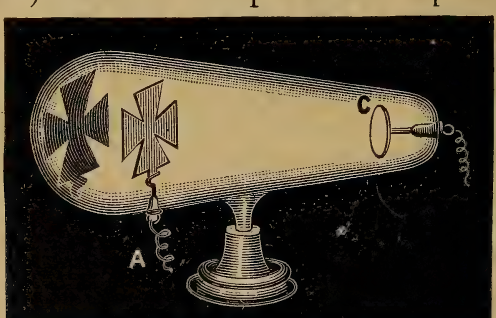

Fig. 172.

the tube. This indicates that the cathode is the source of rays which proceed in straight lines from it. These

rays, known as **cathode rays**, are found to stream out from the cathode at right angles to its surface. Thus a cathode in the form of a flat plate gives a parallel bundle of rays, while a concave cathode gives a convergent, and a convex one, a divergent pencil.

FIG. 173.

The following are some of the properties of the cathode rays:—

(1) They produce luminous effects in certain fluorescent bodies. The light emitted by the tube is due to fluorescent substances in its walls, being green or blue in colour according as the tube is composed of German or lead glass.

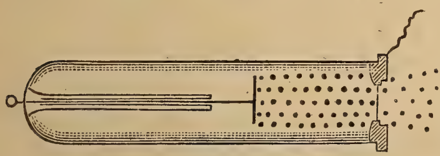

FIG. 174.

Fig. 173 shows a tube lit up by a piece of fluorescent rock placed in the path of the cathode rays.

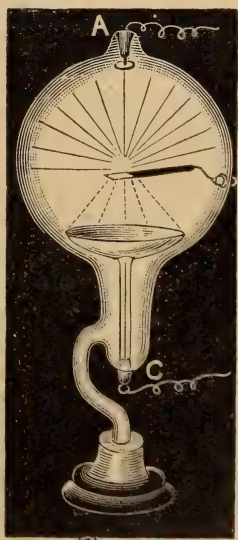

FIG. 175.

(2) The cathode rays are absorbed when they impinge on fairly thick masses of dense matter, but pass readily through thin metal plates, especially through aluminium and other lighter metals. Fig. 174 shows the cathode rays passing through a thin aluminium window placed opposite the cathode.

(3) They heat objects upon which they fall. For example, a thin platinum disc placed at the focus of the convergent rays from a concave cathode may be heated to a white heat (Fig. 175).

(4) They exert pressure on an object on which they impinge. Fig. 176 shows the form of a tube used by Crookes to show the rotation of a wheel by the rays which fall upon its vanes.

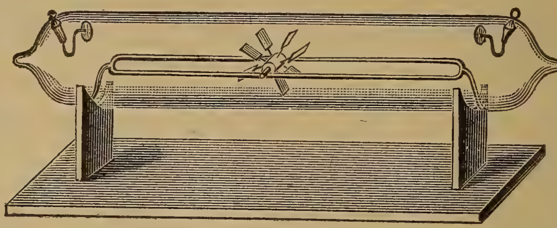

FIG. 176.

(5) The cathode rays are deflected by a magnet. This may be shown by bringing a magnet up to a Crookes tube of the form shown in Fig. 177.

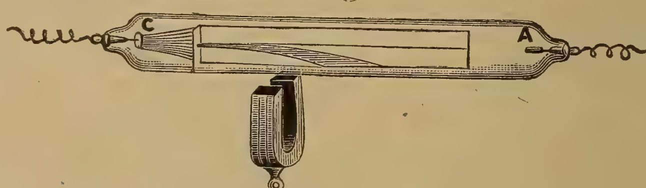

FIG. 177.

The phenomena of the cathode rays is usually explained on the theory that they consist of a stream of electrically charged particles of the residual matter within the tube shot off from the cathode.

These particles, or **electrons,** are probably not greater in mass than the one-thousandth part of the hydrogen molecule. They are negatively charged and move with enormous velocities.

11. Roentgen Rays.

When the cathodic stream impinges upon a dense object, the walls of the tube for example, it gives rise to a new form of radiation generally known as the

Roentgen rays, or **X-rays.** Fig. 178 shows the form of tube now commonly employed for their production. The cathode is concave in form. The anode is a platinum disc so placed as to receive the convergent cathode rays at their focus, which then become the point from which the Roentgen rays proceed.

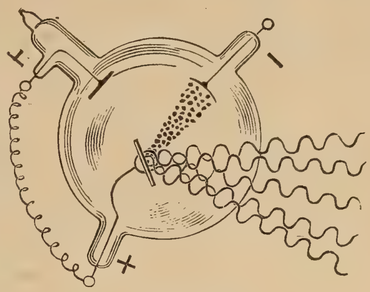

FIG. 178.

The Roentgen rays are now generally regarded as pulsations of ether set up by the bombardment of an object by the rapidly moving electrons of the cathodic stream.

The following are some of the more common properties of these rays:—

(1) They are not reflected or refracted like ordinary light, but pass straight through all substances, being more or less absorbed, according to the density and thickness of the substance.

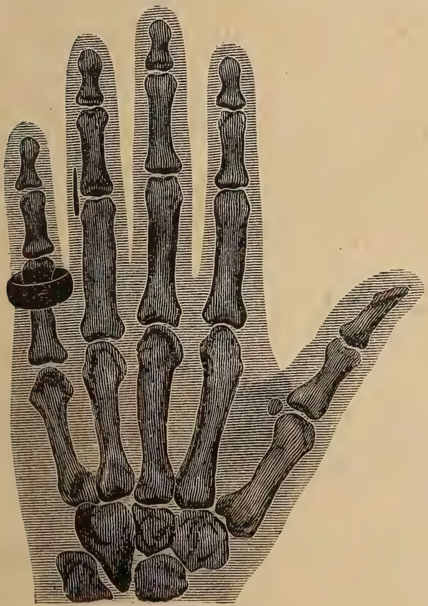

FIG. 179.

(2) They are capable of exciting brilliant fluorescence in certain salts, such as barium platinocyanide and calcium tungstate. The **fluoroscope** used to receive Roentgen ray shadowgraphs consists of a cardboard screen coated with one or the other of the above salts. The screen when

exposed to the action of the rays becomes luminous, and any object opaque to the rays interposed between it and the tube casts a shadow upon it. Fig. 179 shows the shadowgraph of a hand. Since the ring, the needle, the bones and the flesh are of different densities they cast shadows of varying degrees of depth.

(3) The Roentgen rays affect sensitive photographic plates. Permanent images of shadowgraphs can, therefore, be made by substituting a photographic plate, enclosed in its holder, for the fluorescent screen described above.

To make a shadowgraph sharp in outline the object should be placed as near as possible to the screen or plate.

12. Electric Waves.

Hertz discovered that the oscillating spark discharged between the terminals of an induction coil gives rise to electro-magnetic waves in the ether. These waves are probably similar to light, but of much greater wave-length and lower vibration frequency. Hertz used as a detector, to show the presence of these waves, a copper wire of the form shown in Fig. 180. He found that when the wire was supported on an insulating stand in a darkened room, small sparks were seen to pass between the metal knobs at the ends of the wire whenever electric waves were set up by his oscillator. The distances at which waves can be detected by the Hertz method is limited to a few feet.

Fig. 180.

Branly discovered that metal filings, when thrown together loosely and made part of an electric circuit,

have normally a high resistance, but become under the influence of electric waves good conductors. This principle is applied in the construction of the **coherers**, now commonly employed as the detectors of electric waves.

Fig. 181 shows a coherer consisting of a glass tube containing two metallic plugs separated by metallic filings. The coherer is made a part of the circuit by connecting the plugs with the wires.

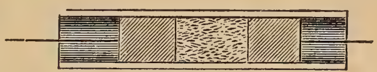

FIG. 181.

The discoveries of Hertz and Branly, demonstrating the possibility of signalling at a distance by electric waves, have lead to the development of the modern system of wireless telegraphy.

13. Wireless Telegraphy.

The following experiments show how electric waves may be set up and detected, and illustrate the principle of wireless telegraphy.

Experiment 3.—To Construct an Oscillator, or Transmitter.

Arrange apparatus as shown in Fig. 182. A, A are brass balls about 4.5 cm. in diameter attached to rods made to slide

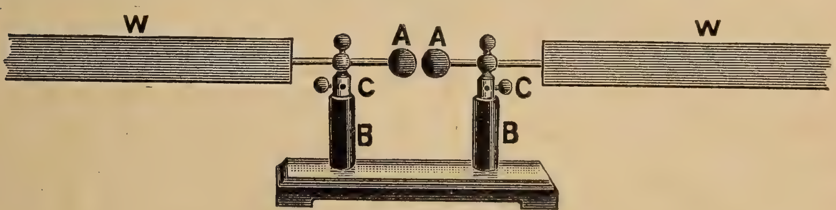

FIG. 182.

through metallic holders C, C, supported on insulating posts B, B. W, W are wings to act as condensers. They may be made of sheet copper and should be at least 50 cm. long and 2 cm. wide.

Adjust the balls A, A so that they will be one or two millimetres apart, and connect C, C with the terminals of an induction coil, giving a spark of at least a quarter of an inch in length.

The oscillatory discharge between the balls will set up electric waves in the ether.

Experiment 4.—To Construct a Receiver.

Arrange apparatus as shown in Fig. 183. A is a coherer which may be made as follows:—Take a heavy glass tube

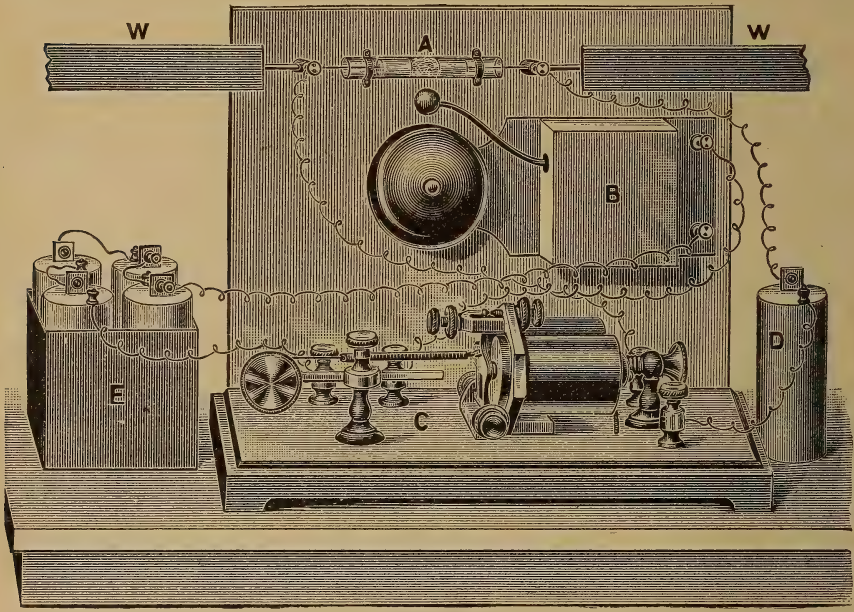

Fig. 183.

about 2 or 3 mm. in diameter and 5 cm. long, and shut up loosely within it, between two bright metallic plugs, fairly coarse filings from a U.S. nickel five cent piece. The plugs should be 2 or 3 mm. apart and be connected with wires as shown in the figure.

B is an electric bell mounted beneath the coherer, on a vertical board, in such a position that when the bell rings the hammer will strike the coherer lightly.

C is a standard relay (Fig. 151, page 197), D and E are batteries, D consisting of one dry cell, and E of three or four similar cells. Fig. 184 shows the way in which the connections

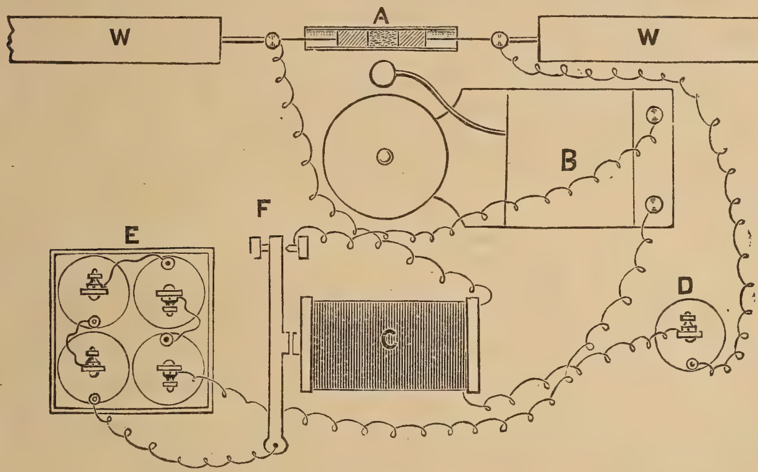

FIG. 184.

are to be made. The coherer is connected in a circuit with the battery D and the coil of the relay; and the bell is connected with the battery E, in a circuit which may be closed or opened at F, by the relay.

W, W are wings, similar to those of the transmitter, connected with wires leading from the coherer.

Adjust the relay and the plugs of the coherer so that a current will be just on the point of moving the armature of the relay.

Place the transmitter a short distance from the receiver, and, by closing the primary circuit of the transmitter, send a spark across the spark-gap between the balls.

Note the effect on the receiver.

The electric waves set up by the transmitter cause the filings in the coherer to become a conductor. The current thus allowed to pass operates the relay, which closes the circuit containing the bell.

When the filings in the coherer once become a conductor, they retain this property until shaken up, therefore the bell would continue to ring after the waves ceased to pass were their sensitive condition not restored at each stroke of the bell-hammer on the coherer. An instrument of the form shown in Fig. 153, page 200, is used instead of the bell when messages are to be transmitted.

The present systems of wireless telegraphy differ mainly in the forms of the coherers used, and in the condenser and "resonance" systems employed to take the place of the wings W, W, used in the above experiments. In Marconi's early experiments, the place of one of the wings was taken by a vertical wire, and that of the other by a wire leading to the ground. While these wires have, in some form, been retained in most systems, other combinations have been introduced which it is not within the limits of this work to describe.

3. The Transformer.

When the primary current is of constantly varying strength, or is an alternating current, the current breaker in the primary circuit is unnecessary, and the apparatus for transforming a current of one electromotive-force to that of another consists of but the two coils and the iron core, as shown in Fig. 185. There are many forms of this instrument but the essential parts of all are the same—two coils and a laminated soft iron core, so placed that as many as possible of the lines of force produced

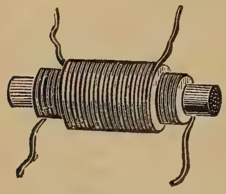

FIG. 185.

by the current in one coil will pass through the space enclosed by the other.

When the current is alternating, the electromotive-forces of the currents generated in the secondary coil are to those of the primary currents nearly in the ratio of the number of turns of wire in the secondary coil to the number in the primary.

4. The Dynamo.

Experiment 2, page 215, shows that it is possible to induce currents in a closed coil by rotating the coil in the field of a magnet.

The object of the dynamo is to make such current available for doing work in an external conductor. This is accomplished by mounting symmetrically on a spindle

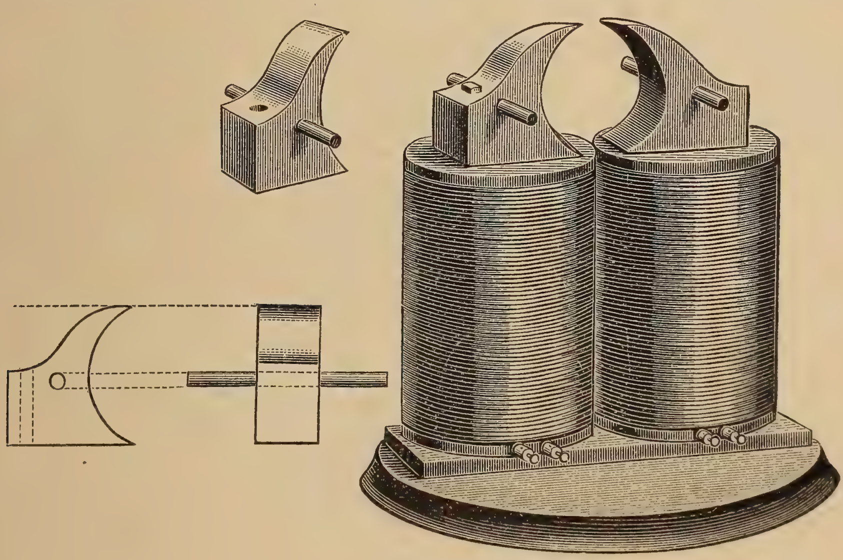

FIG. 186.

a number of connected coils wound on an iron core, and rotating them between the poles of an electro-

magnet. The form of the core and manner of winding the coils differ widely in different types of the machine. One of the first forms in use, and probably the easiest to understand, is that in which the coils are wound around a core in the form of a ring.

The following experiment describes how a dynamo of this type may be constructed, using for the purpose the large electro-magnet described in previous experiments.

Experiment 2.

Provide two cast-iron pole-pieces of the form shown in Fig. 186, to be attached by bolts to the large electro-magnet used in former experiments. The circular opening between the pole-pieces should be about $3\frac{1}{2}$ inches in diameter. Provide also a soft iron ring, about $2\frac{3}{4}$ inches in diameter and of the form shown in Fig. 187. It is best made of soft iron wire, but a ring of solid iron will answer. Insulate the ring by covering it with the insulating tape used for wrapping joints, and

Fig. 187.

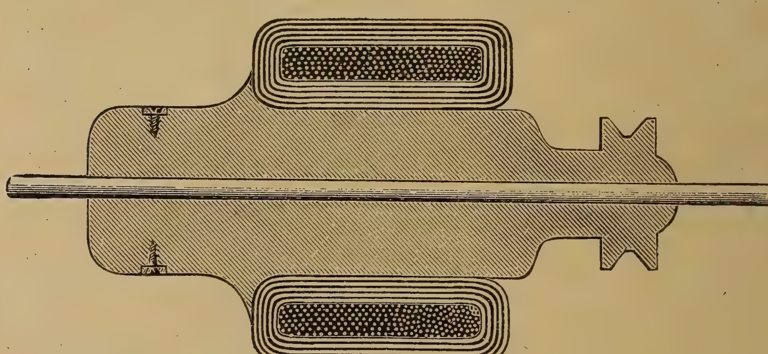

Fig. 188.

wind upon it a number of coils of insulated copper magnet wire No. 20, as shown in Figs. 187, 188. Fit the ring over a

wooden hub, on one end of which is turned a pulley, and through the centre of which passes an iron or brass shaft. Connect the end of each coil with the beginning of the next by fastening the wires to small copper plates screwed to the hub, as shown in Fig. 188. The plates are to be placed side by side, but must not be allowed to touch. Mount the axle on cross bars screwed to the pole-pieces of the large electro-magnet, and attach copper strips, to serve as brushes, to binding posts held in position by a vulcanite bar (Fig. 189). Turn the brushes so that they will just touch the small copper plates, and connect them with a galvanometer. Now connect

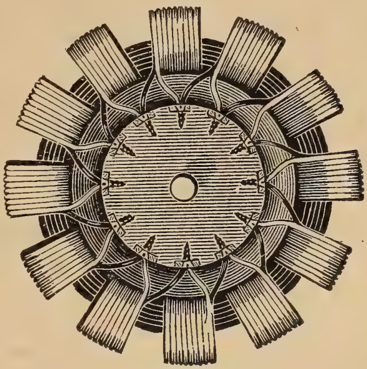

Fig. 188.

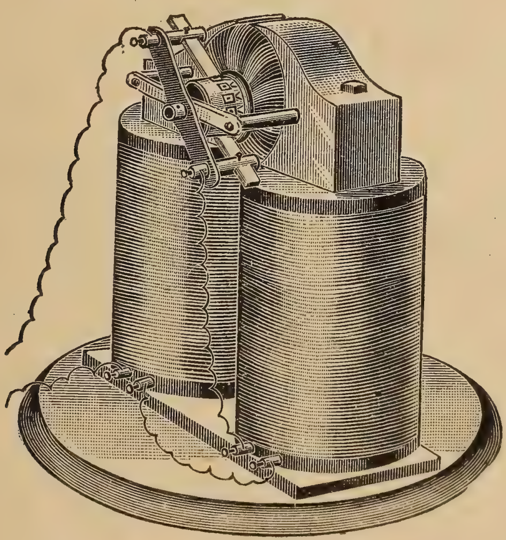

Fig. 189.

the electro-magnet with a battery, and, by means of a whirling-machine, revolve the ring of coils.

1. What evidence have you that the current which passes from one brush to the other through the galvanometer flows always in the same direction?

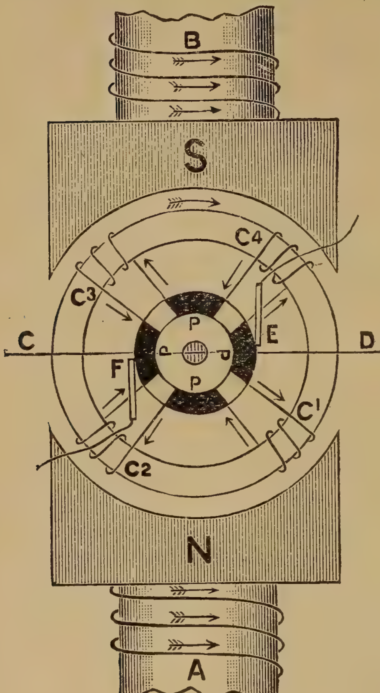

FIG. 190.

2. What is the cause of this current and why does it flow in one direction?

To answer the last question, suppose the iron ring to be revolved between the poles N and S of the electro-magnets A and B (Fig. 190); and, for the sake of simplicity, suppose that the ring contains but four coils, C_1, C_2, C_3, C_4, and that they are in the typical positions shown in the figure.

Consider the conditions of the coils as viewed from one point, say A, along the lines of force in the direction N to S, noting that the currents which would produce the poles N and S both appear from this point to flow clockwise in direction, as marked in the figure.

The maximum number of lines of force pass across a coil when it is crossing the line CD, and the minimum when it is crossing a line drawn from N to S; hence if the ring is revolving clockwise, as shown by the arrow,

1. The number of lines of force passing through the space enclosed by the coil C_1 is decreasing, and a direct (clockwise) current is induced in it.

2. The number of lines of force through the coil C_2 is increasing, and an inverse (contra-clockwise) current is induced in it; but as the coils present opposite ends when viewed from A, it is evident that the current flows in the same absolute direction in C_1 and C_2.

3. The number of lines of force through the coil C_3 is decreasing, and a direct (clockwise) current is induced in it.

4. The number of lines of force through the coil C_4 is increasing, and an inverse (contra-clockwise) current is induced in it; but as C_3 and C_4 present opposite ends when viewed from A, it is evident that the currents flow in the same absolute direction in each, but in a direction opposite to that in the coils C_1 and C_2.

Similarly it can be shown that, whatever the number of coils, the currents in all coils at the one side of the line CD flow in one direction, while those in the coils at the other side of CD flow in the opposite direction.

Hence if the ends of the wires of the coils are connected to copper plates, and brushes are made to bear upon these plates at the points E and F, as required by the experiment and as shown in the figure, a direct, or continuous, current will flow from F to E through a conductor which joins the brushes.

Experiment 3.

Repeat the last experiment, disconnecting the magnet from the battery and connecting it with wires from the brushes, as shown in Fig. 189.

1. Is a current produced when the ring of coils is revolved?
2. If so, how is the magnet excited?

The field-magnets of a dynamo are usually excited by either the whole current or a fraction of the current generated in the armature coils, the cores containing sufficient residual magnetism to cause the machine "to pick up" its current at first.

14. The Direct Current Dynamo.

Experiment 2 illustrates the principle of a dynamo constructed to give a direct, or continuous, current. It may be more explicitly described as follows:—

Construction.

Fig. 191 shows the essential parts of a direct current dynamo. It consists of a **field-magnet** between the poles N, S of which is revolved an **armature,** consisting of a laminated soft iron core A, around which are wound coils C, C, C . . . of insulated copper wire. The ends of these coils are joined to copper **commutator plates** P, P, P . . . as shown in the figure. These plates are insulated from one another and are rubbed at points about midway between the poles by copper or carbon **commutator brushes B, B^1.**

The wires of the main circuit are connected with the brushes, and the field-magnet coils are either connected in **series,** that is, made a part of the main circuit as shown in Fig. 192, or are in a **shunt circuit,** as shown in Fig. 193.

Action.

When the circuit is closed, and the armature revolved, currents will be induced in the connected coils by the constant variations in the number of lines of force passing through the space enclosed by each coil, and will flow

in the directions indicated by the arrows (Fig. 191), as demonstrated in the answer to question 2, page 236. A continuous current, therefore, flows from

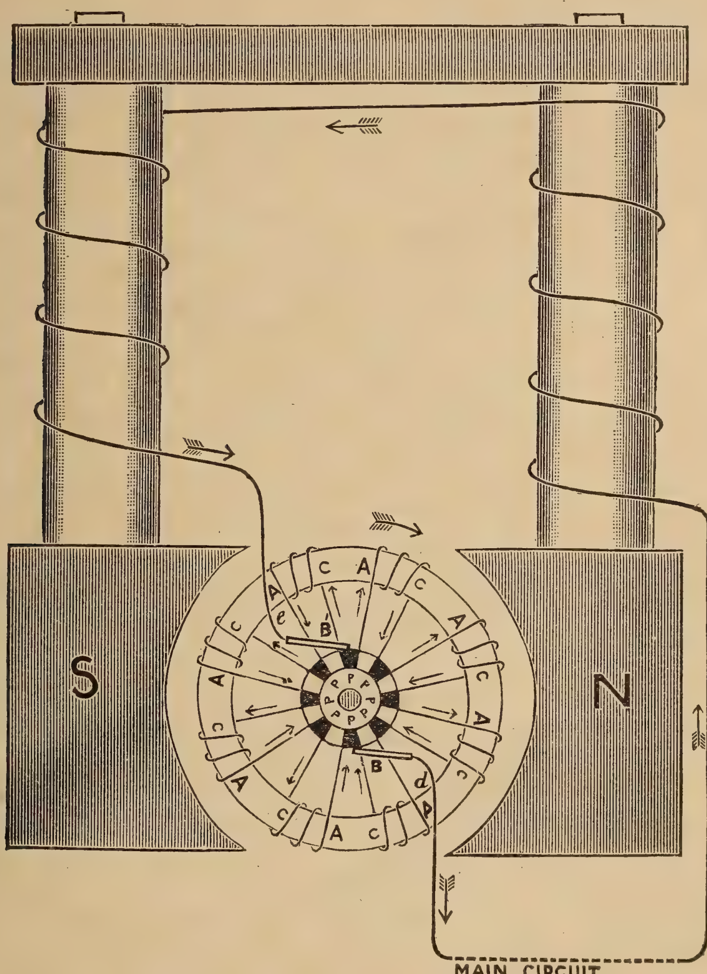

FIG. 191.

the brush which presses the commutator plate at B through the main circuit to the brush which presses the plate at B^1.

In the series dynamo (Fig. 192) the full current excites the field-magnets, which are usually wound with coarse wire. It is used where, as in arc lighting, a constant current is required.

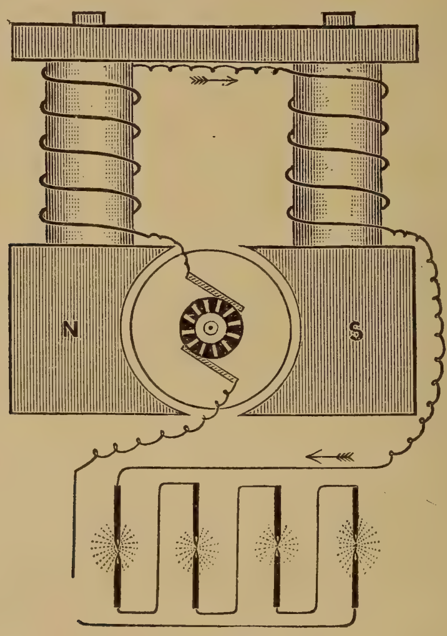

FIG. 192.

In the shunt-dynamo (Fig. 193) a fraction of the current passes directly from one brush through the high resistance field-magnet coils to the other brush. Dynamos of this class are used where the output of current required is continually changing, but where the potential-difference between the brushes must be kept constant. The regulation is accomplished by a suitable rheostat placed in the shunt circuit to vary the amount of the exciting current.

Direct-current dynamos differ mainly in the forms of the armature and the field-magnets.

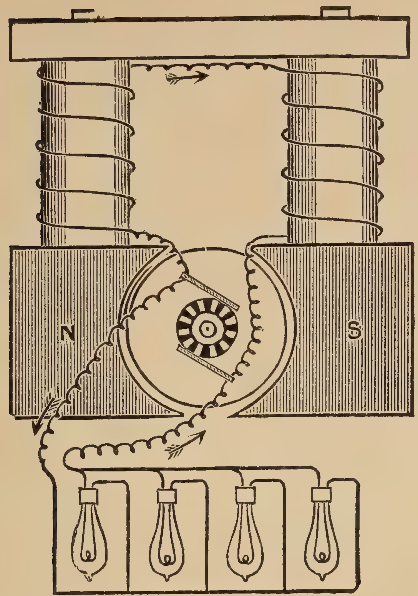

FIG. 193.

15. Forms of Armature.

Most of the armatures in common use are modifications of one or the other of the two following types:—

1. The Gramme Ring Armature.

This is the type described in the foregoing paragraphs and illustrated in Figs. 189 and 191.

2. The Drum Armature.

In this type the coils are wound from end to end around a drum-shaped laminated core. Fig. 194 shows an armature containing four coils wound in this way. As a usual thing the coils are very numerous, and the wire fitted into grooves cut in the core parallel with the shaft.

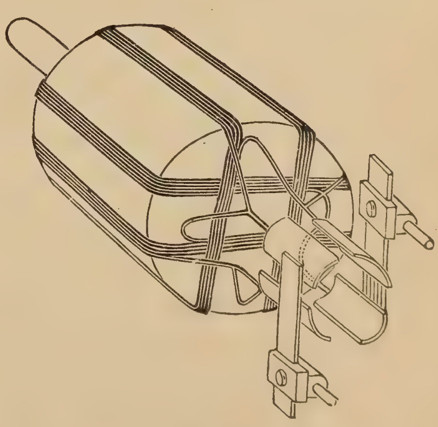

FIG. 194.

The cause and direction of the induced currents may be determined by reasoning similar to that involved in answer to question 2, page 236, as follows:—

For simplicity, suppose the core to contain but one coil connected with commutator plates, as shown in Fig. 195.

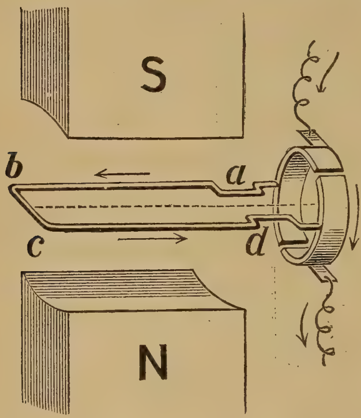

FIG. 195*a*.

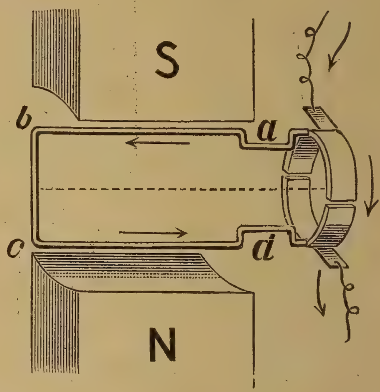

FIG. 195*b*.

Now the maximum number of lines of force pass across the coil when it is in position shown in 195*a*, and the minimum number when in position shown in Fig. 195*b*. In the first quarter-turn, that is, in the change from the position shown in Fig. 195*a* to the position shown in Fig. 195*b*, the number of lines of force passing across the coil is decreasing, and a direct current (clockwise viewed from N) is induced in it. During the next quarter-turn, the number of lines of force through the coil is increasing, and an inverse current (counter-clockwise viewed from N) is induced in it; but as the opposite face of the coil (viewed from N) is presented to view, it is evident that the current flows in the same absolute direction as during the first quarter-turn. In the same way it can be shown that the current continues to flow in one direction in the coil during the second half-turn. But as the sides of the coil, *a b* and *c d*, have changed places,

this direction will be opposite to that of the current in the coil during the first half-turn. In the meantime, the commutator plates have also changed places; hence the current will flow continuously in one direction from brush to brush in the external conductor.

16. Forms of Field-Magnets.

The field-magnets shown in Figs. 189 and 191 are of the bi-polar type. The compact, effective dynamos now in common use are usually supplied with two or more pairs of poles arranged in a ring, with a corresponding pair of collecting brushes for each pair of poles. Fig. 196 shows a modern multi-polar dynamo with drum armature. A—Armature, B—Field-Magnets, C—Dynamo complete.

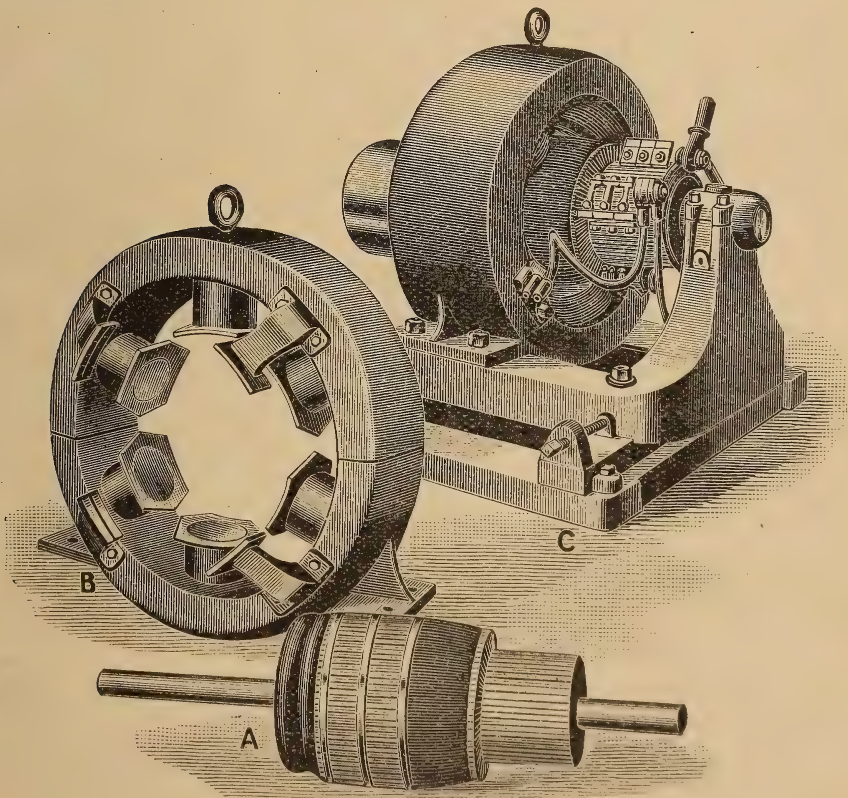

FIG. 196.

17. Alternating Current Dynamo, or Alternator.

Construction.

The current in the armature of a dynamo changes direction at the end of each half revolution of the coil when the field-magnet is bi-polar (see pages 237 and 242), hence, if the two ends of the coil are attached to separate collecting rings (Fig. 197), instead of to commutator plates as in the direct current dynamo, an alternating current will pass through a conductor which joins the brushes bearing upon the rings.

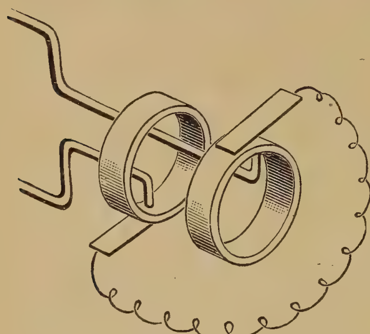

FIG. 197.

In the alternators in common use, a number of connected armature coils A, A, . . . (Fig. 198) are revolved in a multi-polar field. In some of the larger machines the field-magnets are revolved and the armature remains stationary.

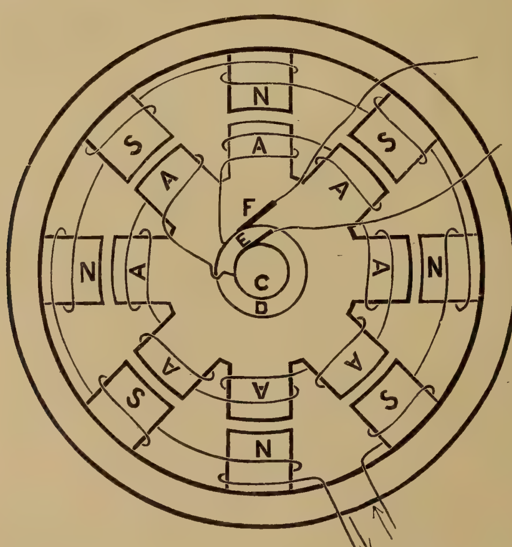

FIG. 198.

The armature coils are equal in number to the poles of the field-magnets. They are wound in alternate directions and are connected in series, with the two free ends of the wire brought to two collecting rings C and D, as shown in the figure.

The fields are excited by a small continuous current dynamo belted to the shaft of the alternator.

Action.

Suppose the ring of armature coils to be opposite the ring of field coils and to be revolving in either direction. Applying the laws of induction as in pages 236 and 242, it is evident, (1) that, in moving to the next position in which the coils will be similarly situated, the induced current in each coil will be in such a direction as to produce a continuous current in the whole series of coils, which will flow from one collecting ring to the other; (2) that during the next similar change of position a continuous current will again flow through the series of coils, but in the opposite direction. Consequently, as the armature is revolved, an alternating current will flow through the external conductor joining the brushes E and F.

Since the number of alternations of this current for each revolution of the armature equals the number of poles in the field-magnet, the number of alternations per minute is equal to the number of poles in the field-magnet multiplied by the number of revolutions made by the armature per minute.

18. Uses of the Alternating Current.

On account of the facility with which the E.M.F. of an alternating current may be changed by a transformer

(page 232), alternating currents are now usually employed whenever it is found necessary or convenient to change frequently the tension of a current. The most common illustrations are to be found in the case of the long distance transmission of electricity, where the currents generated by the dynamos are transformed into currents of very high E.M.F. to overcome the high resistance of the transmission wires and again into currents of lower tension for use at the centres of distribution; and in the case of incandescent lighting, where it is advisable to have currents of fairly high tension on the street wires but, for the sake of safety and economy, currents of low E.M.F. in the lamps and house connections.

QUESTIONS.

1 Upon what is the potential-difference between the brushes of a dynamo dependent?

2. To what is the internal resistance of a dynamo due?

3. How should a dynamo for producing currents at a high electromotive-force be wound?

4. How should a dynamo used to produce a current for electroplating be wound?

5. What would be the effect of short-circuiting (1) a series dynamo, (2) a shunt dynamo? Explain.

6. What would be the effect upon the potential-difference between the brushes of a dynamo of moving them backward or forward around the ring of commutator plates? Explain.

7. Why are the armature coils wound on an **iron** coil? Why is the core laminated?

8. What would be the effect upon the working of a dynamo of connecting the commutator plates by binding a bare copper wire around them, (1) if the field-magnet coils are in a shunt circuit, (2) if the field-magnet is excited by a separate dynamo? Would a current be generated in either of these cases? If so, where would it flow?

5. The Electric Motor.

The direct current dynamo may be used as a **motor.** The armature and field-magnet coils are wound to suit the electromotive-force of the current used.

Action of the Dynamo as an Electric Motor.

The current supplied to the motor divides at *d*, Fig. 199; part flows through the field-magnet coils and part

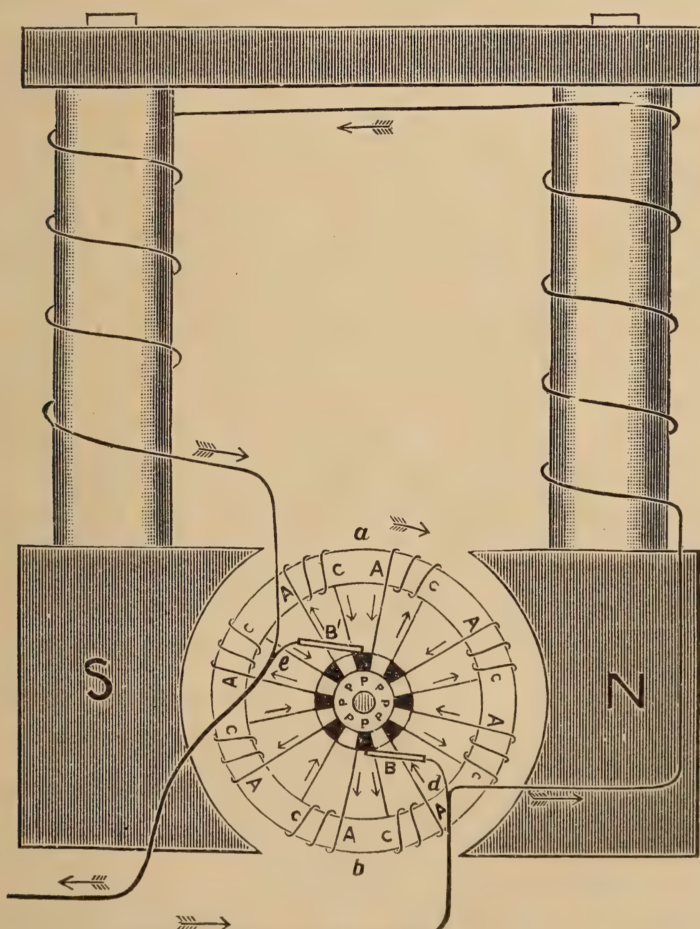

FIG. 199.

enters the armature coils by the brush D at the point *b*, where it divides, part passing through the coils on one side of the ring, and part through the coils on the other side. The currents through the armature coils re-unite at *a*, pass out by the brush B^1, and are joined at *e* by the part of the main current which flows through the field-magnet coils.

Both the field-magnet and the armature cores are thus magnetized, and poles are formed according to the law stated in Art. 5, page 190. The poles of the field-magnet are as indicated in the figure. Each half of the iron core will be an electro-magnet of the horse-shoe type, having a south pole at *a* and a north pole at *b*.

The mutual attractions and repulsions between the poles of the armature and the field-magnet cause the armature to revolve.

Trace as far as you can the transferences and transformations of energy in the following :—

A printing press is driven by an electric motor to which the current is supplied by a dynamo driven by a steam engine.

6. The Telephone.

The telephone instruments described in Art. 9, page 316, Part I., are those at present in common use in Ontario.

Fig. 200 shows the essential parts of the transmitter used in the "long distance" instruments.

V is the mouth-piece, D the metallic diaphragm, B a carbon button attached to the diaphragm, B^1 another carbon button attached to the frame of the instrument

opposite to B. The space between the carbon buttons is filled with loosely packed, coarse, granulated carbon.

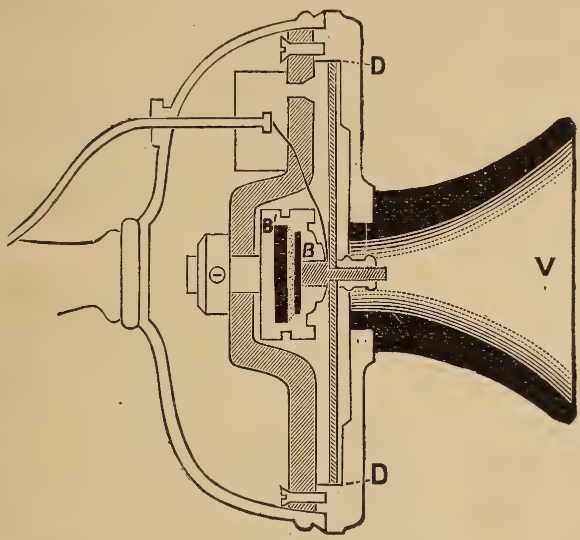

FIG. 200.

Fig. 201 shows the electrical connection in the complete circuit.

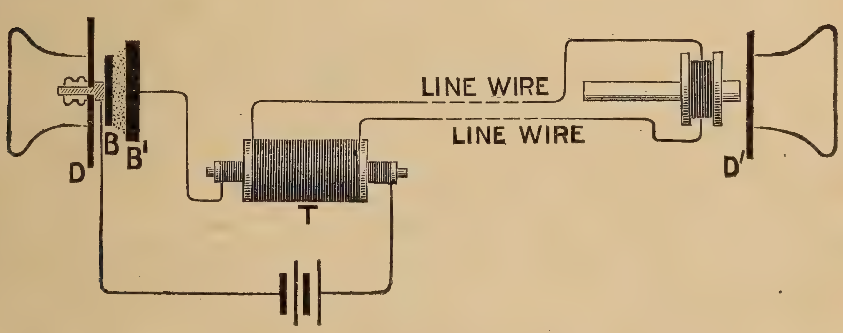

FIG. 201.

The transmitter acts on the principle that the conductivity of the granular carbon varies with the varying pressure exerted upon it by the button B as the diaphragm vibrates under the action of the sound-waves. The current passing from the battery through the primary

coil of the transformer T will, therefore, be fluctuating in character, and will induce a current of varying strength, but of higher electro-motive force, in the secondary coil connected in the main line with the receiver. This current will cause corresponding variations in the magnetic state of the electro-magnet of the receiver, and thus set up vibrations in its diaphragm which will reproduce the sound-waves that caused the diaphragm of the transmitter to vibrate.

In the original Bell telephone the transmitter and receiver were similar to the receiver described above, and the two coils were connected by wires without a battery. Explain how this transmitter generates a current, and give the reasons for the vibration of the diaphragm in the receiver.

CHAPTER XVI.

HEATING AND LIGHTING EFFECTS OF THE ELECTRIC CURRENT.

I.—The Electric Current and Heat.

Experiment 1.

Connect three or four cells of a battery as shown in Fig. 202. Attach a copper wire to each pole, and complete the circuit by attaching to the free end of one of the copper wires a piece of fine platinum or iron wire four or five inches

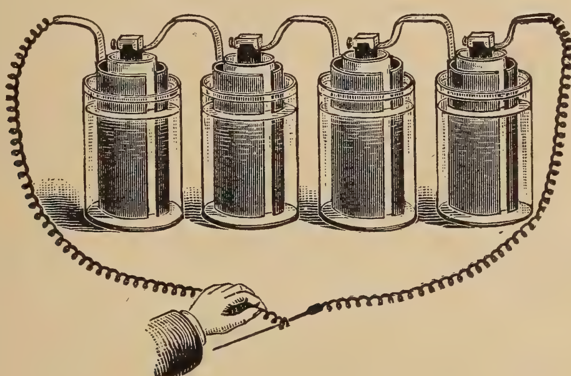

Fig. 202.

long, and touching the end of the other copper wire to the end of the platinum or iron wire. (The fine iron wire used by florists answers well.) Slide the copper wire along the iron wire up toward the other copper wire.

What evidence have you of the production of heat?

Experiment 2.

Find by trial the length of a fine wire that your battery will heat red-hot, and place a piece about one-half this length in a circuit with the battery and a rheostat. Regulate the current with the rheostat so that the wire will again be just

red-hot. Increase the current by decreasing the resistance in the circuit.

What effect has increasing the current upon the temperature of the wire?

Experiment 3.

Place a piece of wire about one-third the length of that which your battery will heat red-hot in a circuit with the battery, a rheostat, and a tangent galvanometer or ammeter (galvanometer graduated to read in amperes). Regulate the current with the rheostat so that the wire will again be just red-hot. Now increase the length of the wire gradually, keeping the wire as nearly as possible at the same temperature by decreasing the rheostat resistance in the circuit. Observe the current strength required to heat to the same temperature each length of wire.

1. Is any additional current required to heat the increased length of wire?

2. How will the potential-difference between the two ends of the short wire compare with that between the two ends of the longer wire when they are both heated to the same temperature? Why?

Whenever an electric current meets with resistance in a conductor, heat results; and, as no body is a perfect conductor of electricity, a certain amount of the energy of the electric current is always transformed into the energy of molecular motion.

Joule, who has investigated this subject, found, by comparing the results of numerous experiments, that **the number of units of heat developed in a conductor varies as:—**

(1) **Its resistance.**

(2) **The square of the strength of the current.**

(3) **The time the current flows.**

1. Practical Applications.

Resistance wires heated by an electric current are used for a variety of purposes, such as performing surgical operations, igniting fuses, cooking, heating electric cars, etc.

Rods of metal are welded by pressing them together with sufficient force while a strong current of electricity is passed through them. Heat is developed at the point of junction, where the resistance is the greatest, and the metals are softened and become welded together.

II.—The Electric Current and Light.

There are two systems of electric lighting, the incandescent and the arc.

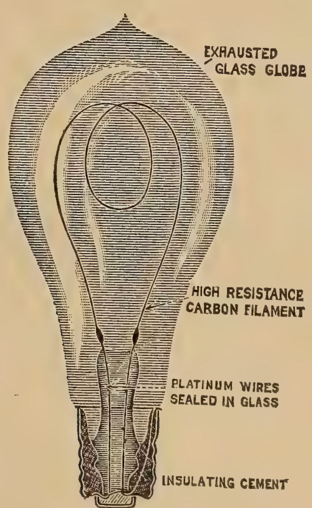

FIG. 203.

1. The Incandescent Lamp.

Construction.

Fig. 203 shows the construction of the incandescent lamp. A carbon filament, made by carbonizing a thread

of bamboo or other fibre at a very high temperature, is attached to conducting wires and enclosed in a pear-shaped glass globe, from which the air is then exhausted. The conducting wires are of platinum where they are fused into the glass.

Action.

When a sufficient current is passed through the high resistance carbon filament, it is heated to incandescence and yields a bright, steady light. The carbon is infusible, and does not burn for lack of oxygen to unite with it.

Grouping of Lamps.

All the lamps to be used in the same circuit are so constructed as to give their proper candle-power when the same potential-difference is maintained between their terminals. This is generally from 100 to 110 volts. The lamps are connected in multiple, or parallel, that is, the current from the leading wires divides, and a part flows through each lamp, as shown in Fig. 193. The dynamo is regulated to maintain a constant potential-difference between the leading wires.

If each lamp (Fig. 193) requires one-half of an ampere of current to raise it to its proper candle-power, what current flows through each of the following wires: (1) from the brushes of the dynamo to the first lamp, (2) between the first and second lamps, (3) between the third and fourth lamps?

2. The Arc Lamp.

2. The Arc Light.

When two carbon rods, or pencils, are connected by conductors with the poles of a sufficiently powerful battery or dynamo, touched together, and then separated a short distance, the current continues to flow across the the gap, developing intense heat and raising the terminals to

incandescence, thus producing a powerful light, generally known as the **arc light.**

Explanation.

When the carbon points are separated by air only, the potential-difference between them, when connected with the poles of an ordinary arc-light dynamo, is not sufficient to cause a spark to pass, even when they are very close together; but when they are in contact, and then separated while the current is passing through them, the "extra current" spark, produced on separation, volatilizes a small quantity of the carbon between the points, and a conducting medium, consisting of carbon vapour and heated air, is thus produced, through which the current continues to flow.

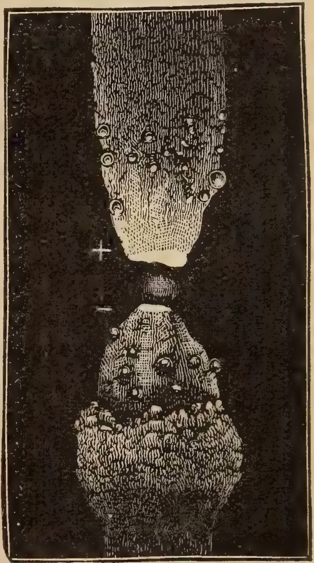

FIG. 204.

Since this medium has a high resistance, intense heat is developed and the carbon points become vividly incandescent, and burn away slowly in the air. When a direct current is used, the point of the positive carbon becomes hollowed out in the form of a crater, and the negative one becomes pointed, as shown in Fig. 204.

The greater part of the light is radiated from the carbon points, the positive one being the brighter.

The Enclosed Arc.

The open arc is now being largely superseded by the "enclosed arc," a form in which the carbon points are enclosed in a globe with an air-tight joint at the bottom

(Fig. 205) and with but sufficient opening at the top to give the upper carbon freedom. Since the oxygen in the globe soon becomes exhausted, and the absence of draft prevents its renewal, the carbons of the enclosed arc burn away very slowly. As a usual thing they last about ten times as long as when burning in the open air.

Grouping, Regulation, Etc.

Arc lamps are usually connected in series, that is, the negative carbon of one lamp is connected with the positive carbon of the next, as shown in Fig. 192, and a constant current flows from one pole of the dynamo through each of the lamps to the other pole.

Regulators for maintaining a constant distance between the carbon points as they burn away, are of a great variety of patterns. In most of them the regulation is accomplished by the action of two electro-magnets or solenoids. Fig. 205 shows an enclosed arc lamp with its regulator. M is a solenoid, wound with coarse wire, connected in series with the carbons. N is an electro-magnet with two windings, one of coarse wire in series with the solenoid and the carbons, and the other of many turns of fine wire in a shunt between the carbons. Fig. 205*c* shows the way in which the connections are made. Since the current in the shunt passes around the core of N in a direction opposite to that in the coarse wire series coil, it tends to neutralize its magnetic effects.

When the carbons are together and the circuit closed, the current passes through the coarse wire winding of the magnet N, the solenoid M, and across the carbon C

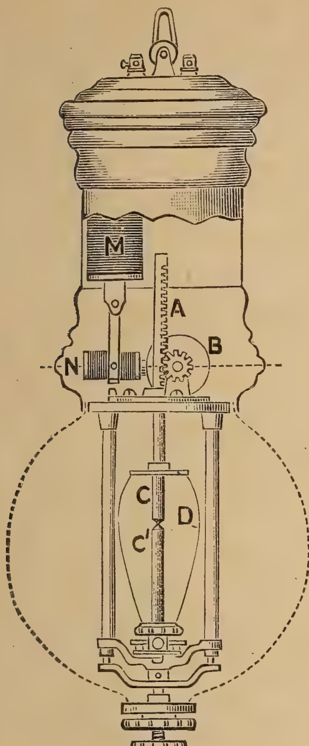

FIG. 205*a*.

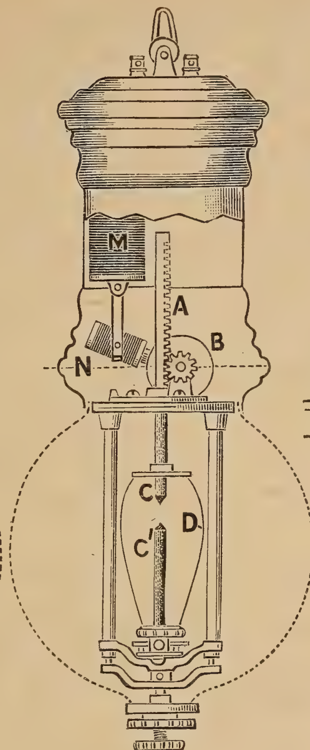

FIG. 205*b*.

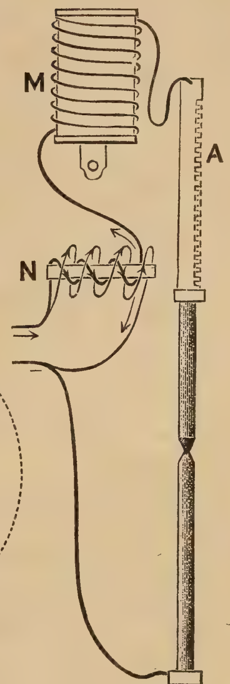

FIG. 205*c*.

and C′ to the conductor. The solenoid M draws up the iron plunger supporting the magnet N, while at the same time N grips the circular armature B, and, in being lifted, turns it on its axis. The small pinion attached to B is turned, and the rack A bearing the carbon holder is raised. The carbons are thus separated and the arc formed. As the carbons burn away and the potential-difference between them increases, sufficient current is shunted through the fine wire high resistance winding of N to demagnetize the core and free the armature B. The upper carbon then drops by its own weight and shortens the length of the arc. The distance between the points is thus kept fairly constant.

The electromotive-force required for an open arc light is about 50 volts, and for an enclosed arc from 75 to 80 volts. The current used in the open arc is commonly from 6 to 10 amperes, and from $3\frac{1}{2}$ to 6 amperes in the enclosed arc.

If a current of 10 amperes passes through each lamp (Fig. 192), where there are four lamps in series, what current passes from the one brush of the dynamo to the other?

CHAPTER XVII.

ELECTRICAL MEASUREMENTS.

I.—Ohm's Law.

We have learned that the **strength of a current**, or the **quantity of electricity which flows past a point in a circuit in one second,** is dependent on the E.M.F. of the current and the resistance of the circuit. The exact relation among these quantities was first enunciated by Ohm. It may be thus stated:—

1. Ohm's Law.

The current varies directly as the electromotive-force and inversely as the resistance of the circuit.

Practical Unit.

The **unit resistance** is the **ohm,** which may be defined as the resistance of a uniform column of mercury 106.3 cm. long and 1 square millimetre in section, at 0°C.

The **unit current** is the **ampere,** which may be defined as a current which deposits silver at the rate of 0.001118 grams per second.

The **unit electromotive-force** is the **volt,** which is that E.M.F. that will cause a current of one ampere to flow in a circuit whose resistance is one ohm.

If **C** is the measure of a current in amperes, **R**, the resistance of the circuit in ohms, and **E**, the electromotive-force, Ohm's Law may be expressed as follows:—

$$C = \frac{E}{R}.$$

QUESTIONS.

1. The electromotive-force of a battery is 10 volts, the resistance of the cells 10 ohms, and the resistance of the external circuit 20 ohms. What is the current?

2. The difference in potential between a trolley wire and the rail is 500 volts. What current will flow through a conductor which joins them if the total resistance is 1,000 ohms?

3. The potential-difference between the terminals of an incandescent lamp is 104 volts when one-half an ampere of current is passing through the filament. What is the resistance?

4. A dynamo, the E.M.F. of which is 4 volts, is used for the purpose of copper-plating. If the resistance of the dynamo is $\frac{1}{100}$ of an ohm, what is the resistance of the bath and its connections when a current of 20 amperes is passing through it?

5. What must be the E.M.F. of a battery to ring an electric bell which required a current of $\frac{1}{10}$ ampere, if the resistance of the bell and connection is 200 ohms, and the resistance of the battery 20 ohms?

6. What must be the E.M.F. of a battery required to send a current of $\frac{1}{100}$ of an ampere through a telegraph line 100 miles long if the resistance of the wires is 10 ohms to the mile, the resistance of the instruments being 300 ohms, and of the battery 50 ohms, if the return current through the earth meets with no appreciable resistance?

7. The potential-difference between the carbons of an arc lamp is 50 volts and the resistance of the arc 2 ohms. If the arc exerts an opposing E.M.F. of its own of 30 volts, what is the current passing through the carbons?

8. A dynamo, of which the E.M.F. is 3 volts, is used to decompose water. What is the total resistance in the circuit when a current of one-half an ampere passes through it, if the counter electromotive-force of polarization of the electrodes is 1.5 volts?

9. On adding 3 ohms to the resistance of a certain circuit the current is diminished in the ratio of 6 to 5. What was the original resistance, and how much should be added to this in order to bring the current down to half its original value?

10. The current along a telegraph line is tested at two stations whose respective distances from the sending battery are 50 and 150 miles. The current in the latter case is one-half that in the former. If the galvanometer has a resistance equal to that of 15 miles of the line wire, prove that the battery resistance is equal to that of 35 miles of wire.

11. A dynamo gives an E.M.F. of 840 volts when running at the rate of 750 revolutions per minute, and its internal resistance is 12 ohms. Show that such a machine can supply 16 arc lamps in series, each lamp offering a resistance of 4.5 ohms, and requiring a current of 10 amperes.

---

2. Fall of Potential in a Circuit.

If a battery or dynamo is generating a current in a circuit, it is evident that the E.M.F. required to maintain this current in the whole circuit is greater than that required to overcome the resistance of a part of the circuit. For example, if the total resistance is 100 ohms, and the E.M.F. is 1000 volts, the current in the circuit is 10 amperes. Here an E.M.F. of 1000 volts is required to maintain a current of 10 amperes against a total resistance of 100 ohms, and it is manifest that to maintain this current in the part of the circuit of which the resistance is, say 50 or 75 ohms, an E.M.F. of but 500 or 750 volts will be required. This is usually expressed by saying that there is a fall in potential in the part of the circuit whose resistance is 50 ohms of 500 volts, and in the part of the circuit whose resistance is 75 ohms of 750 volts.

In general, if there is a closed circuit through which a current is flowing, **the fall in potential in any portion of the circuit is proportional to the resistance of that portion of the circuit.**

Experiment.

If your laboratory is supplied with a voltmeter, that is, a galvanometer wound and graduated to indicate directly in volts the difference in potential between two points of a circuit, measure the differences in potential between different parts of any circuit in which a current is flowing, and compare them with one another.

QUESTIONS.

1. The end, A, of the wire ABC is connected with the earth, and the difference in potential between the other end, C, and the earth is 100 volts. If the resistance of the portion AB is 9.6 ohms and that of BC 2.4, what current will flow along the wire, and what will be the potential-difference between the point B and the earth?

2. The poles of a battery are connected by a wire 8 metres long, having a resistance of one-half an ohm per metre. If the E.M.F. of the battery is 7 volts and the internal resistance 10 ohms, find the distance between two points on the wire such that the potential-difference between them is 1 volt. What is the current in the wire?

3. The potential difference between the brushes of a dynamo supplying current to an incandescent lamp is 104 volts. If the resistance in the wires on the street leading from the dynamo to the house is 2 ohms, that of the wires in the house 2 ohms, and that of the lamp 204 ohms, what is the fall in potential in (1) the wires on the street, (2) the wires in the house, and what is the potential-difference between the terminals of the lamp?

4. The potential-difference between the brushes of a dynamo supplying a current of 10 amperes to 38 arc lamps connected in series is 2000 volts. If the fall in potential in the connecting wires in the circuit is equal to the fall in two lamps, what is the fall in potential in a single lamp, and what is the resistance in the connecting wires?

5. A cell has an internal resistance of 0.3 ohms, and its E.M.F. on open circuit is 1.8 volts. If the poles are connected by a conductor

whose resistance is 1.2 ohms, what is the current produced, and what is the potential-difference between the poles of the cell?

6. The E.M.F. of a battery on open circuit is 15 volts. When the poles are connected by a copper wire a current of 1.5 amperes is produced, and the potential-difference between the battery poles falls to 9 volts. Find the resistance of the wire and the internal resistance of the battery.

II.—Measurement of Resistance.

3. Wheatstone Bridge.

The resistance of a conductor is usually measured by an instrument called a Wheatstone Bridge. It consists of a series of resistance coils made of German silver wire connected by conductors arranged in three sets A, B, and C, with connections for a battery, a galvanometer, and the resistance to be measured, as shown in Fig. 206.

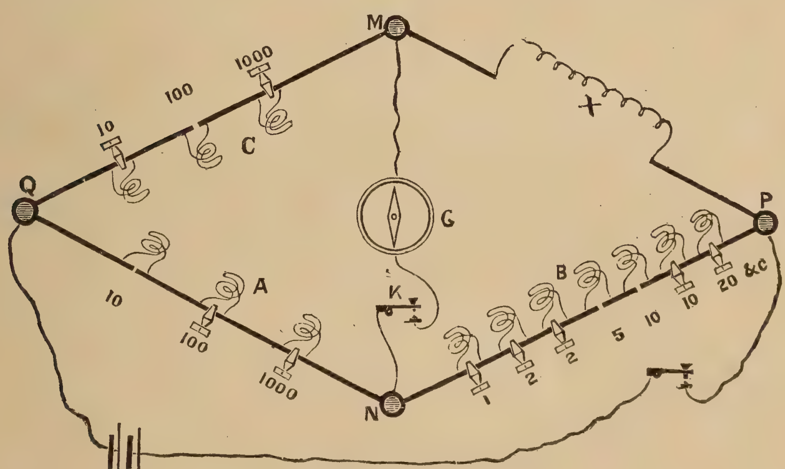

FIG. 206.

The coils are mounted in a box, and the changes in the resistance are made by inserting or withdrawing conducting plugs, as shown in Fig. 207.

The branches A and C usually have three coils each, the resistances of which are respectively 10, 100 and 1000 ohms, and the branch B has a combination of coils which will give any number of units of resistance from 1 to 11,110 ohms. The conductor whose resistance (X)

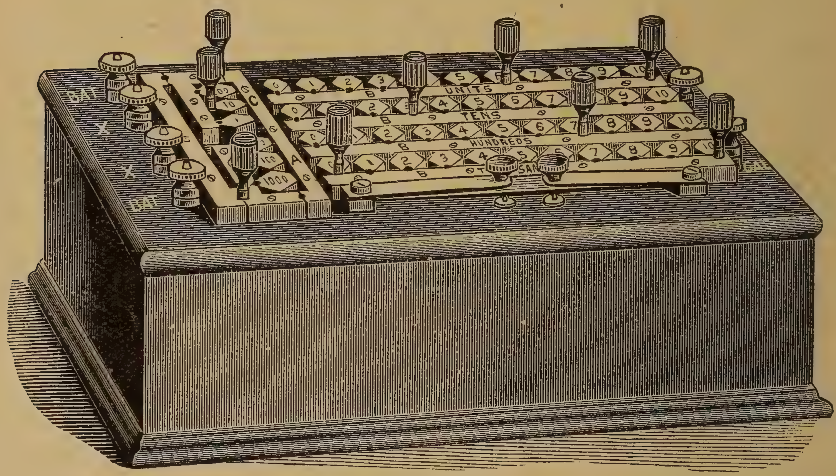

FIG. 207.

is to be measured is inserted in the fourth branch of the bridge (Fig. 206), and the resistances A, B, and C adjusted until the galvanometer connecting M and N stands at zero when the keys are closed.

Then the current in the battery is flowing from P, partly through X and C and partly through B and A, to Q, and since no current flows from M to N, the potential of M must be the same as that of N, therefore the fall in potential from P to M in the circuit PMQ must equal the fall in potential from P to N in the circuit PNQ; but the fall in potential in a part of a circuit is proportional to the resistance of that portion of the circuit (Art. 2, page 261).

Hence $$\frac{X}{C} = \frac{B}{A}$$

or $$X = \frac{B \times C}{A}$$

The resistances A, B and C are read from the coils, and the calculations made.

Experiment 1.

Measure with a wheatstone bridge the resistance of your galvanoscope, the coils used in Experiment 2, page 212, an incandescent lamp, etc.

Experiment 2.

Place two copper electrodes a distance apart in a solution of copper sulphate, and measure with the wheatstone bridge the resistance between them.

Would the result of the experiment be the same if platinum electrodes of the same size were used? If not, why?

4. Laws of Resistance.

Experiment 3.

Measure with the wheatstone bridge the resistances of pieces of the same wire whose lengths are proportional to 1, 2, 3, etc.

1. In what proportions are the resistances?

2. What is the relation between the length of a wire and its resistance?

Experiment 4.

Repeat Experiment 2, keeping the areas of the part of the electrodes immersed constant, and varying the distance between them.

How does an increase in the distance between the electrodes affect the resistance of the liquid conductor between them?

Experiment 5.

Measure with a screw caliper, or obtain from a table, the diameters of several copper wires of different sizes, and calculate

the area of the cross-section of each. Measure the resistances of the wires.

What is the relation between the area of the cross-section of a wire and its resistance?

Experiment 6.

Repeat Experiment 2, keeping the distance between the electrodes constant, and varying the areas of the parts immersed.

How does increasing the areas of the parts of the electrodes immersed affect the resistance of the liquid conductor between them?

Experiment 7.

Obtain two wires, one of iron and one of copper, of the same size and length, and measure the resistance of each.

How many times does the resistance of the iron contain the resistance of the copper?

The above experiments and others of a similar nature verify the following laws:—

5. Laws of Resistance.

1. **The resistance of a conductor varies directly as its length.**

2. **The resistance of a conductor varies inversely as the area of its cross-section. In a round conductor, therefore, the resistance varies inversely as the square of the diameter.**

3. **The resistance of a conductor of given length and cross-section depends upon the material of which it is made.**

6. Specific Resistance.

The resistance of a prism of length 1 cm. and cross-section 1 sq. cm. of any substance is the **resistivity,** or

specific resistance, of that substance. It is generally estimated in microhms, or millionths of an ohm.

If l denotes the length of a conductor in centimetres, A the area of its cross-section in square centimetres, ρ its specific resistance, and R its resistance, by the laws of resistance

$$R = \frac{l\rho}{A}.$$

What will l and A represent in the case of a liquid conductor ?

7. Resistance and Temperature.

Experiment 8.

Place in the circuit with a battery a galvanoscope and a short piece of fine platinum or iron wire. Observe the deflection of the needle of the galvanoscope, and heat the platinum wire with a spirit lamp or a Bunsen burner.

1. What change takes place in the current ?
2. How can you account for it ?

The resistance of nearly all pure metals increases about 0.4 per cent. for each increase in temperature of 1°C. The resistance of carbon diminishes on heating. The resistance of an electrolyte also decreases with increase in temperature.

QUESTIONS.

1. Copper wire one-twelfth of an inch in diameter has a resistance of 8 ohms per mile. What is the resistance of a mile of copper wire the diameter of which is $\frac{1}{36}$ in. ?

2. If the resistance of a yard of iron wire, 0.03 inches in diameter, is 0.197 ohms, what is the resistance of 15 miles of iron wire 0.3 inches in diameter ?

3. What is the resistance of a column of mercury 2 metres long and 0.6 of a square millimetre in cross-section at 0°C. ?

4. The resistance at 0° of a column of mercury 1 metre in length and 1 sq. mm. in cross-section is called a "Sieman's unit." Find the value of this unit in terms of the ohm.

5. A mile of telegraph wire 2 mm. in diameter offers a resistance of 13 ohms. What is the resistance of 440 yards of wire 0.8 mm. in diameter made of the same material?

6. If the resistance at 0°C. of an iron wire 1 foot long and weighing 1 grain be 1.08 ohms, find the resistance of 0°C. of 1 mile of iron wire weighing 300 lbs.

7. What length of copper wire, having a diameter of 3 millimetres, has the same resistance as 10 metres of copper wire, having a diameter of 2 millimetres.

8. On measuring the resistance of a piece of No. 30 B.W.G. (covered) copper wire, 18.12 yards long, I found it to have a resistance of 3.02 ohms. Another coil of the same wire had a resistance of 22.65 ohms; what length of wire was there in the coil?

9. The resistance of a bobbin of wire is measured and found to be 68 ohms; a portion of the wire 2 metres in length is now cut off, and its resistance is found to be 0.75 ohms. What was the total length of wire on the bobbin?

10. Two wires of the same length and material are found to have resistances of 4 and 9 ohms respectively. If the diameter of the first is 1 mm., what is the diameter of the second?

11. What must be the thickness of copper wire which, taking equal lengths, gives the same resistance as iron wire 6.5 millimetres in diameter, the specific resistance of iron being six times that of copper?

12. Two separate pounds of copper of the same quality are drawn out into uniform wires, the one twice the length of the other. Find the ratio between their resistances.

13. Two exactly equal pieces of copper are drawn into wire, one into a wire 10 feet long, and the other into a wire 20 feet long. If the resistance of the shorter wire is 0.5 ohms, what is the resistance of the longer wire?

14. A piece of copper wire 100 yards long weighs 1 lb.; another piece of copper wire 500 yards long weighs $\frac{1}{4}$ lb. What are the relative resistances of the two wires?

15. Find the length of an iron wire one-twentieth of an inch in diameter which will have the same resistance as a copper wire one-sixtieth of an inch in diameter and 720 yards long, the conducting power of copper being six times that of iron.

16. A wire made of platinoid is found to have a resistance of 0.203 ohms per metre. The cross-section of the wire is 0.016 sq. cm. Express the specific resistance of platinoid in microhms.

17. Taking the specific resistance of copper as 1.642, calculate (1) the resistance of a kilometre of copper wire whose diameter is 1 millimetre; (2) the resistance of a copper conductor one square centimetre in area of cross-section, and long enough to reach from Niagara to New York, reckoning this distance as 480 kilometres.

18. Two Grove cells, alike in all respects except that in one the plates are twice as far apart as in the other, are arranged in series, and the poles of the battery so constituted are united by a copper wire. The liquid in both cells becomes heated. In which is the rise in temperature the greater, and why?

19. A current flows through a copper wire, which is thicker at one end than the other. If there is any difference either (1) in the strength of the current at, or (2) in the temperature of, the two ends of the wire, state how they differ from each other, and why.

III.—Resistance in Divided Circuit—Shunts.

8. Problem.

Two conductors, A and B (Fig. 208), maintained at a constant difference of potential E, are joined in parallel by two wires whose resistances are respectively R_1 and R_2; find (1) the resistance of a single wire equivalent to the two in parallel, (2) the fraction of the total current which flows through each wire.

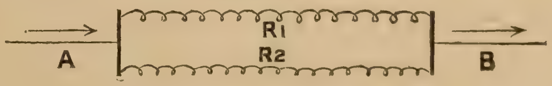

FIG. 208.

(1) The current through the first wire $= \frac{E}{R_1}$

" " " " second " $= \frac{E}{R_2}$

Total current through the two wires $= \frac{E}{R_1} + \frac{E}{R_2}$

But the total current $= \frac{E}{R}$, where R is the resistance of a single wire equivalent to the two.

Therefore $\frac{E}{R} = \frac{E}{R_1} + \frac{E}{R_2}$;

that is, $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$, or $R = \frac{R_1 R_2}{R_1 + R_2}$

It is evident from the above solution that the **reciprocal of the resistance equivalent to any number of conductors in parallel is equal to the sum of the reciprocals of their separate resistances.**

(2) The fraction of the total current in the first wire

$$= \frac{\frac{E}{R}}{\frac{E}{R_1} + \frac{E}{R_2}} = \frac{R_2}{R_1 + R_2}$$

Similarly, the fraction of the total current in the second wire

$$= \frac{R_1}{R_1 + R_2}.$$

9. Shunts.

When it is undesirable to send the whole current to be measured through a galvanometer or other current-measuring instrument, a definite fractional part of the current is diverted by making the instrument one of two parallel conductors in the circuit, as shown in Fig. 209.

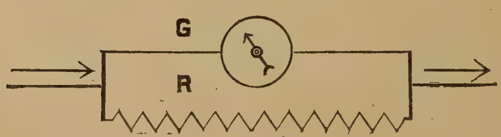

FIG. 209.

The conductor R in parallel with the galvanometer G is called a **shunt.**

If G is the resistance of the galvanometer, R the resistance of the shunt, and C the total current, the amount of current through the galvanometer

$$= \frac{R}{G + R} \times C. \quad \text{(Art. 8, page 270).}$$

For the sake of facility in calculation, it is usual to make R $\frac{1}{9}$, $\frac{1}{99}$, or $\frac{1}{999}$ of G, when, by the above formula, the current through the galvanometer will be $\frac{1}{10}$, $\frac{1}{100}$, or $\frac{1}{1000}$ of the total current to be measured.

QUESTIONS.

1. The poles of a voltaic battery are connected by two wires in parallel. If the resistance of the one is 10 ohms and that of the other 20 ohms, find (1) the resistance of a single wire equivalent to the two in parallel; (2) the proportion of the total current passing through each wire.

2. Find the total resistance when the following resistances are joined in series:—$3\frac{1}{2}$ ohms, $2\frac{1}{3}$ ohms, $2\frac{1}{4}$ ohms. What would be the joint resistance if the resistances were joined in parallel?

3. What must be the resistance of a wire joined in parallel with a wire whose resistance is 12 ohms, if their joint resistance is 3 ohms?

4. The joint resistance of ten similar incandescent lamps connected in multiple is 10 ohms. What is the resistance of a single lamp?

5. Four incandescent lamps are joined in parallel on a 100-volt circuit. If the resistances of the lamps are respectively 100 ohms, 200 ohms, 300 ohms and 400 ohms, find (1) the total current passing through the group of lamps; (2) the proportion of the total current passing through the first lamp; (3) the resistance of a single lamp which would take the same current as the group.

6. A galvanometer whose resistance is 1,000 ohms is used with a shunt. If $\frac{1}{11}$ of the total current passes through the galvanometer, what is the resistance of the shunt?

7. If the shunt of a galvanometer has a resistance of $\frac{1}{n}$ of the galvanometer, what fraction of the total current passes through the galvanometer?

8. The internal resistance of a Daniell's cell is 1 ohm; its terminals are connected (*a*) by a wire whose resistance is 4 ohms, (*b*) by two wires in parallel, one of the wires having a resistance of 4 ohms, the resistance of the other wire being 1 ohm. Compare the currents through the cell in the two cases.

IV.—Grouping of Cells or Dynamos.

Cells or dynamos may be combined in various ways to give a current. The methods may be classified as follows:—

1. Series Arrangement.

10. Series Arrangement Defined.

Electrical generators are connected in series, or tandem, when the negative pole of the one is connected directly with the positive pole of the next (Fig. 210).

11. Effect of Series Arrangement on the Internal Resistance.

If n cells are arranged in series, and r is the internal resistance of each cell, it is evident that **the resistance of the group** $= n\,r$, because the current has to pass through a liquid conductor n times as long as that between the plates of a single cell.

12. Effect of Series Arrangement on E.M.F.

If the potential-difference between the plates of a single cell (Fig. 210) is e, the potential difference between Z_1 and C_1 is e; but when C_1 and Z_2 are connected by a short thick conductor there is practically no

fall in potential between them, therefore the potential-difference between Z_1 and Z_2 is e. Again, the potential-difference between Z_2 and C_2 is e, therefore the potential-difference between Z_1 and C_2 is $2e$. Similarly, for 3, 4, etc., cells the potential-differences are respectively $3e$, $4e$, etc. Hence **the E.M.F. of n cells in series is $n\,e$.**

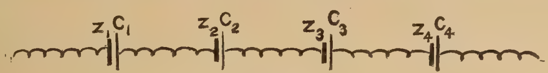

FIG. 210.

13. The Current Given by Series Arrangement.

By Ohm's Law

$$C = \frac{E}{R}$$

but $E = n\,e$, and $R = n\,r + R_1$ where n is the number of cells, e the E.M.F. and r the internal resistance of each, and R_1 the external resistance in the circuit.

Hence

$$C = \frac{n\,e}{n\,r + R_1}.$$

2. Multiple Arrangement.

14. Multiple Arrangement Defined.

Generators are connected in multiple, or parallel, when all the positive poles are connected to one conductor, and all the negative poles to another, as shown in Fig. 211.

15. Effect of Multiple Arrangement on the Internal Resistance.

If n cells are arranged in multiple, and r is the internal resistance of a single cell,

$$\textbf{the internal resistance of the group} = \frac{r}{n}$$

because the current in passing through the liquid from one set of plates to the other has n paths opened up to

it, and therefore the sectional area of the column of liquid traversed is n times that of one cell, hence the resistance is only $\frac{1}{n}$ of that of one cell. (Law 2, page 266).

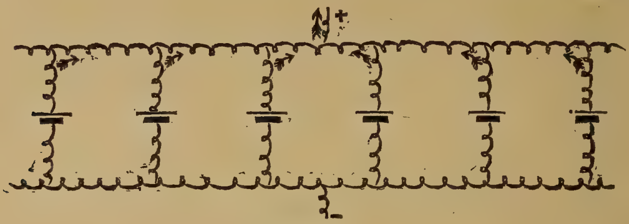

FIG. 211.

16. Effect of Multiple Arrangement on E.M.F.

When all the positive plates are connected they are of the same potential; for a similar reason all the negative plates are the same potential, hence **the E.M.F. of n cells in multiple is the same as that of one cell.**

This method of grouping has the effect of transforming a number of single cells into one large cell, the Z plates being united to form one large Z plate, and the C plates to form one large C plate. It must be remembered that **the potential-difference between the plates of a cell is independent of the size of the plates.**

Upon what is this potential-difference dependent?

17. The Current Given by Multiple Arrangement.

$$C = \frac{E}{R}$$

but $E = e$ and $R = \frac{r}{n} + R_1$,

where n is the number of cells, e the E.M.F. and r the internal resistance of each, and R_1 the external resistance.

Hence

$$C = \frac{e}{\frac{r}{n} + R_1}$$

3. Multiple-Series Arrangement.

Sometimes both methods of arrangement are simul-

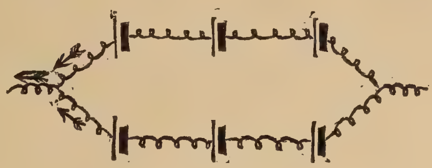

FIG. 212.

taneously employed, as shown in Figs. 212, 213.

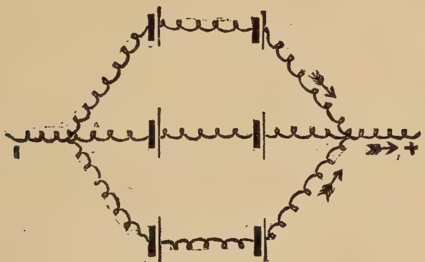

FIG. 213.

18. Current Given by Multiple-Series Arrangement.

To determine the current given by a number of cells grouped in multiple-series, consider each group in multiple as a single cell, and determine the current given by these groups when connected in series.

Thus, if n is the total number of cells, r is the internal resistance and e the E.M.F. of each cell, and m the number grouped in multiple,

$$\text{the E.M.F. of each group in multiple} = e$$

$$\text{and the internal resistance} \qquad = \frac{r}{m}$$

but there are $\frac{n}{m}$ such groups connected in series.

Hence

$$C = \frac{\frac{n}{m}e}{\frac{r}{m} \times \frac{n}{m} + R_1} = \frac{\frac{n}{m}e}{\frac{nr}{m^2} + R_1}$$

$$= \frac{ne}{\frac{nr}{m} + m R_1}$$

Where R_1 is the external resistance in the circuit. **The internal resistance of all the cells when grouped in this way is**

$$\frac{nr}{m^2}.$$

19. Best Arrangement of Cells.

It is manifest that when the external resistance is very great as compared with the internal resistance, to overcome the resistance, the electromotive-force must be increased, even at the expense of increasing the internal resistance, and the series arrangement of cells is the best. When the external resistance is very low as compared with the internal resistance, the object of the grouping is to lower as far as possible the internal resistance, and the multiple arrangement is the best. Between these extremes of high and low external resistance some form of multiple-series grouping gives the strongest current.

A general rule for determining the best method of grouping in any case may be found as follows:—

Let n denote the number of cells,

r, the internal resistance of each cell,

e, the E.M.F. of each cell,

R_1, the external resistance,

m, the number of cells in a multiple group when the current is a maximum.

Then

$$C = \frac{n\,e}{\frac{n\,r}{m} + m\,R} \qquad \text{(Art. 15.)}$$

$$= \frac{n\,e}{\left(\sqrt{\frac{n\,r}{m}} - \sqrt{m\,R_1}\right)^2 + 2\sqrt{n\,r\,R_1}}$$

C is a maximum when the denominator

$$\left(\sqrt{\frac{n\,r}{m}} - \sqrt{m\,R_1}\right)^2 + 2\sqrt{r\,n\,R_1}$$

is a minimum: but this quantity is a minimum when

$$\left(\sqrt{\frac{n\,r}{m}} - \sqrt{m\,R_1}\right)^2$$

is a minimum because $2\sqrt{r\,n\,R_1}$ is constant, since r, n, and R_1 remain always the same.

Now $\left(\sqrt{\frac{n\,r}{m}} - \sqrt{m\,R_1}\right)^2$ is a minimum when it equals zero, because a square cannot be less than zero.

Therefore the current is at a maximum when

$$\left(\sqrt{\frac{n\,r}{m}} - \sqrt{m\,R_1}\right)^2 = 0$$

or $$\sqrt{\frac{n\,r}{m}} - \sqrt{m\,R_1} = 0$$

or $$\frac{n\,r}{m} = m\,R_1$$

or $$\frac{n\,r}{m^2} = R_1\,;$$

but $\frac{n\,r}{m^2}$ is the internal resistance of the cells.

Hence

For a given external resistance the maximum current is obtained when the internal resistance is equal to the external resistance.

When $$\frac{n\,r}{m^2} = R_1,$$

$$m = \sqrt{\frac{n\,r}{R_1}}.$$

Or

The current is a maximum when the cells are so arranged that the number in each group in multiple

$$= \sqrt{\frac{\textbf{internal resistance of one cell} \times \textbf{total number of cells}}{\textbf{external resistance}}}.$$

20. Example.

What is the best way of arranging a battery of 18 cells, each having a resistance of 1.8 ohms, so as to send the strongest current through an external resistance of 1 ohm; and what is the current?

The number in each group in multiple

$$= \sqrt{\frac{n\,r}{R}} = \sqrt{\frac{18 \times 1.8}{1}} = 5.69.$$

Since 6 is the factor of 18 nearest 5.69, the cells are to be arranged in 3 groups, in each of which 6 cells are joined in multiple, the groups being joined in series.

The E.M.F. of each group = 1 volt

and the internal resistance $= \frac{1.8}{6} = .3$

$$C = \frac{E}{R} = \frac{3 \times 1}{.3 \times 3 + 1} = 1.57 \text{ amperes.}$$

QUESTIONS.

1. 50 Grove's cells (E.M.F. of a Grove cell = 1.8 volts) are united in series, and the circuit is completed by a wire whose resistance is 15 ohms. Supposing the internal resistance of each cell to be 0.3 ohms calculate the strength of the current.

2. Eight cells, each with half an ohm internal resistance, and 1.1 volts E.M.F., are connected (*a*) all in series, (*b*) all in parallel, (*c*) in two parallel sets of four cells each. Calculate the current sent in each case through a wire of resistance 0.8 ohm.

3. Ten voltaic cells, each of internal resistance 2 ohms and electromotive-force 1.5 volts, are connected (*a*) in a single series, (*b*) in two series of five each, the like ends of the two series being joined together. If the terminals are in each case connected by a wire whose resistance is 10 ohms, show what is the strength of the current in the wire in each case.

4. You have 20 large Leclanché cells (E.M.F. $=1.5$ volts, $r=0.5$ ohms each) in a circuit in which the external resistance is 10 ohms. Find the strength of the current which flows (*a*) when the cells are joined in single series; (*b*) all the zincs are united and all the carbons united, in parallel arc; (*c*) when the cells are arranged in groups of 2 in multiple; (*d*) when the cells are arranged in groups of 4 in multiple.

5. The current from a battery of 4 equal cells is sent through a tangent galvanometer, the resistance of which, together with the attached wires, is exactly equal to that of a single cell. Show that the galvanometer deflection will be the same whether the cells are arranged all in multiple or all in series.

6. You are required to send a current of 2 amperes through an electro-magnet of 3.5 ohms resistance, and are supplied with a number of Grove cells, each of 1.9 volts E.M.F. and 0.25 ohms internal resistance. How many cells are required?

7. Calculate the number of cells required to produce a current of 50 milli-amperes (one one-thousandth of an ampere), through a line 114 miles long, whose resistance is $12\frac{1}{2}$ ohms per mile, the available cells of the battery having each an internal resistance of 1.5 ohms, and an E.M.F. of 1.5 volts.

8. A current of not less than 0.016 amperes is to be sent through an external resistance of 360 ohms. What is the smallest number of Leclanché cells, each with E.M.F. 1.4 volts and resistance 15 ohms, by which this can be effected? What would be the maximum strength of current obtainable if double this number of cells were used?

9. The wire used on Indian telegraph lines is iron wire of No. 2 B.W.G., having a resistance of 4.6 ohms per mile. The batteries consist of cells of 1.04 volts E.M.F. and 30 ohms resistance per cell. Assuming that the resistance of the instruments is 80 ohms, and that a current of 8 milli-amperes is required to work them, find how many cells should be employed on a line 200 miles in length.

10 How would you arrange a battery of 12 cells, each of 0.6 ohms internal resistance, so as to send the strongest current through an electro-magnet of resistance 0.7 ohms?

11. Find the best arrangements of 24 cells having an external resistance of 3 ohms, each cell having an internal resistance of 2 ohms.

12. You have a battery of 48 Daniell cells, each of 6 ohms internal resistance, and are required to send the strongest possible current through an external resistance of 15 ohms; how would you group the cells? Find also the current produced and the difference of potential between the poles of the battery, assuming that the E.M.F. of a Daniell cell is 1.07 volts.

13. You are supplied with 12 exactly similar cells, the internal resistance of each of which is one-fourth of the external resistance of the circuit: how would you group the cells so as to obtain the maximum current?

14. If you wish to heat a platinum wire, at a distance from the battery, to as high a temperature as possible, what sort of connecting wires will you use, and why? And what arrangement of battery-cells will you adopt?

If in the last case the insulation of the conducting wires was very imperfect, show whether it would be better to increase the number of cells arranged in series, or the number arranged in parallel; supposing that you have some additional cells at your disposal.

15. A circuit is formed of six similar cells in series and a wire of 10 ohms resistance. The E.M.F. of each cell is 1 volt and its resistance 5 ohms. Determine the difference of potential between the positive and negative poles of any one of the cells.

16. Six Daniell cells, for each of which $E = 1.05$ volts, $r = 0.5$ ohms, are joined in series. Three wires X, Y, and Z, whose resistances are severally 3, 30, and 300 ohms, can be inserted between the poles of the battery. Determine the current which flows when each wire is inserted separately; also determine that which flows when they are all inserted at once in parallel.

17. The poles of a battery consisting of 40 Daniell cells in series are connected by a resistance of 280 ohms, and the current produced is 0.535 amperes; when the external resistance is increased to 1080 ohms the current is reduced to one half: find the average resistance and E.M.F. of each cell of the battery, and determine the difference of potential existing between the poles of the battery when the external resistance is 280 ohms.

18. A Daniell cell, the internal resistance of which is 0.3 ohms, works through an external resistance of 1 ohm. What must be the resistance of another Daniell cell so that when it is joined up in series with the first and working through the same external resistance the current shall be the same as before? If the cells are joined up in parallel how will the current be modified?

ANSWERS TO QUESTIONS.

Page 16.

2. .952 sec.
4. (1) (*a*) 1103.843 ft. per sec.;
   (*b*) 1109.729 ft. per sec.;
   (*c*) 1129.24 ft. per sec.
   (2) 890.522 ft. per sec.
   (3) 4149.63 ft. per sec.
   (4) 4.703 sec.
5. 819°.
6. 419.9. m. per sec.
7. 15.004 sec.
8. 1118.04 ft. per sec.
9. 4700 ft. per sec.
10. 6716.58 ft.
14. $1109\frac{1}{3}$ ft. per sec.
15. 30.34. in.

Page 25.

1. 4.123 sec.
2. 2801.3 ft.
3. 112.924 ft.

Page 32.

3. 52 in.; $1109\frac{1}{3}$ ft. per sec.
4. 33,792 cm. per sec.

Page 43.

1. 1, $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, etc.
3. 1, $\frac{8}{9}$, $\frac{4}{5}$, $\frac{3}{4}$, etc.
5. W, $\frac{81}{64}$ W, $\frac{25}{16}$ W, etc.
6. 1, $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, etc.
7. Equal.
8. 80 pds.
9. Divided by 2.
10. From C to G.
11. G of third octave above.
12. Vibration-number will be halved.
13. $3\sqrt{10.5} : \sqrt{7.8}$.

Page 57.

1. $7\frac{1}{2}$ in.
2. 1126.4 ft. per sec.
3. 8.59 in.; 34.37 in.
5. 3:2.
6. 41.55 cm.; 124.65 cm.; 207.75 cm.; 83.1 cm.; 166.2 cm.; 249.3 cm.

PAGE 74.

1. 9:4.
2. 72:5.
3. 121:400.
5. 16.
6. 2 ft. from candle.

PAGE 94.

2. 12 cm.
3. 20.93 in.
4. 12 in.; 36 in. in front of mirror; 18 in. in front of mirror; 24 in. behind the mirror.

PAGE 260.

1. $\frac{1}{3}$ ampere.
2. $\frac{1}{2}$ ampere.
3. 208 ohms.
4. .19 ohms.
5. 22 volts.
6. 13.5 volts.
7. 10 amperes.
8. 3 ohms.
9. 15 ohms; 15 ohms.

PAGE 262.

1. $8\frac{1}{3}$ amperes; 80 volts.
2. 4 metres; $\frac{1}{2}$ ampere.
3. 1 volt; 1 volt; 102 volts.
4. 50 volts; 10 ohms.
5. 1.2 amperes; 1.44 volts.
6. 6 ohms; 4 ohms.

PAGE 267.

1. 72 ohms.
2. 52.008 ohms.
3. 3.13 ohms.
4. 0.9434 ohms.
5. 20.31 ohms.
6. 14.337 ohms.
7. 22.5 m.
8. 135.9 yds.
9. $181\frac{1}{3}$ m.
10. 0.6 mm.
11. 2.653 mm.
12. 4:1.
13. 2 ohms.
14. 1:100.
15. 1080 yds.
16. 3.04.
17. (1) 20.9 ohms; (2) 78.8 ohms.

PAGE 271.

1. $16\frac{2}{3}$ ohms; $\frac{2}{3}$; $\frac{1}{3}$.
2. $8\frac{1}{2}$ ohms; $\frac{12}{97}$ ohms.
3. 4 ohms.
4. 100 ohms.
5. $2\frac{1}{2}$ amperes; $\frac{12}{25}$ amperes; 48 ohms.
6. 10 ohms.
7. $\frac{1}{n+1}$.
8. 9:25.

PAGE 278.

1. 3 amperes.
2. $1\frac{5}{6}$ amperes; $1\frac{19}{69}$ amperes; $\frac{4}{9}$ amperes.
3. $\frac{1}{2}$ ampere in each case.
4. (*a*) 1.5 amperes, (*b*) 0.1496 ampere, (*c*) 1.2 amperes, (*d*) 0.702 ampere.
6. 5 cells.
7. 50 cells.
8. 5 cells in series; 0.027 ampere.
9. 10.
10. 3 cells in each group in multiple.
11. 6 cells in each group in multiple.
12. 4 cells in each group in multiple; 0.39 ampere; 5.85 volts.
13. 3 cells in each group in multiple.
15. 0.75 volts.
16. Through X, 1.05 amperes; through Y, 0.1909 ampere; through Z, 0.0207 ampere; through all three 1.105 amperes.
17. 1.07 volts; 13 ohms; 14.98 volts.
18. 1.3 ohms.

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